Process Simulation of Aluminium Sheet Metal Deep Drawing at Elevated Temperatures

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Abstract. Lightweight design is essential for an economic and environmentally friendly vehicle. Aluminium sheet metal is well known for its ability to improve the strength to weight ratio of lightweight structures. One disadvantage of aluminium is that it is less formable than steel. Therefore complex part geometries can only be realized by expensive multi-step production processes. One method for overcoming this disadvantage is deep drawing at elevated temperatures. In this way the formability of aluminium sheet metal can be improved significantly, and the number of necessary production steps can thereby be reduced. This paper introduces deep drawing of aluminium sheet metal at elevated temperatures, a corresponding simulation method, a characteristic process and its optimization. The temperature and strain rate dependent material properties of a 5xxx series alloy and their modelling are discussed. A three dimensional thermomechanically coupled finite element deep drawing simulation model and its validation are presented. Based on the validated simulation model an optimised process strategy regarding formability, time and cost is introduced.

Keywords: aluminium sheet metal, deep drawing, warm forming, thermo-mechanical finite element simulation, process design
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INTRODUCTION

Climate change, energy saving and emission reduction have never been discussed more lively than nowadays. Part of this discussion is the future way of individual mobility. Researchers and engineers are looking for the most efficient way to power automotive vehicles. Independently of the future drivetrain technology, lightweight construction will play a key role for the design of an energy efficient vehicle. Regarding this, aluminium sheet metal is well known for its potential to improve the strength to weight ratio of thin-walled lightweight structures.

Intelligent lightweight construction integrates multiple functions within one structural part and therefore requires complex shapes. Due to its low formability in comparison to steel, aluminium often cannot fulfil these demands. To overcome this problem numerous methods have been developed to improve the formability of aluminium sheet metal.

Hydroforming for example can improve the strain distribution in the sheet metal during forming. In this way strain localization and thus fracture can be avoided. Numerous researchers have shown that hydroforming has positive effects on formability and feasibility of complex shapes. Disadvantages are additional process equipment like a high pressure liquid and sealing and advanced process control [1].

Another technology to enhance the forming limits of aluminium sheet metal is superplastic forming (SPF). Superplasticity is a state in which solid material can be deformed over 200 % during tensile deformation. In the SPF process gas pressure is used to blow aluminium sheet metal into complex shapes at temperatures up to 550°C. The main advantages of the process are feasibility of very tight radii, complex shapes and deep draws as well as avoidance of springback. Due to the fact that SPF only works at very low strain rates of about 10^{-3} s^{-1} the major

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disadvantage is the considerable higher cycle time in comparison to conventional forming methods. Therefore the application of SPF in automotive industry is very restricted. Another disadvantage is that only particular fine grained alloys can be used [2].

The ductility of common aluminium alloys increases with temperature. Thus forming at elevated temperatures close to the recrystallization temperature of about 300 °C, also called warm forming, is another promising method to improve formability[1]. Warm forming of aluminium is investigated since the 1950's and has become more interesting for researchers during the oil crises in the 1970's. Ayres and Wenner [3] and Shehata et al. [4] were amongst the first to investigate warm forming of AlMg alloys scientifically and described the changing of material properties with increasing temperature. They investigated that flow stress is significantly reduced and stated that the improvement in formability is due to increased strain rate hardening and increased limit strains. In the 1990's Schmoeckel [5] showed the positive effects of elevated temperature for deep drawing of AlMg4.5Mn0.4 sheet metal. It was demonstrated that the formability can be improved by a uniform temperature increase, but the best results were obtained by heating the flange area and keeping the punch at a lower temperature. In this way, the resistance against deformation in the flange, where the material is highly deformed, is reduced. As a result the drawing force decreases. The potential failure area near the punch radius, which has to withstand the drawing force, is cooled and thus relatively strong. Therefore the ratio of transmittable force and drawing force can be increased and higher drawing depths can be achieved. Li and Ghosh [6] proofed these observations for additional AlMg alloys. For more information Tebbe and Kridli [7] and particularly Toros et al. [8] published detailed reviews of the state of the art in warm forming of aluminium sheet metal.

The reason why warm forming is of particular interest for the industry is that there are the following advantages in comparison to hydroforming and SPF: Additional process equipment like a liquid or a gas is not required. Process control is easier and the variety of usable sheet metal alloys is wider. The major disadvantage is that there is very little experience with this process technology available. Thus engineers rely on expensive trial and error development. Therefore numerical simulation using the Finite Element Method (FEM), which is nowadays almost indispensable for the design of a cold sheet metal forming process, is even more important for warm forming.

As mentioned above, it has been proofed that in warm forming it is preferable to set the flange temperature higher than the punch temperature. That means that there are time dependent temperature gradients in the sheet metal. Therefore an accurate warm forming simulation has to be thermomechanically coupled and has to incorporate flow stress and strain rate dependency on temperature [9]. So far researchers often had to focus on simulation of simplified isothermal and/or two-dimensional forming processes with very small deformation rates. Since hot forming of boron steel sheet metal becomes more important, the corresponding simulation techniques have been improved as well. One finite element solver that offers adequate methods for advanced simulation of thermomechnically coupled processes is LS-Dyna [10] [11]. So far these methods have not been used to investigate deep drawing of aluminium sheet metal at elevated temperatures.

The aim of this work is to show the application of state of the art thermomechanically coupled simulation methods and their validation for warm forming of a 5xxx series aluminium sheet metal alloy. Based on a validated simulation model a warm forming process simulation is set up and optimised. The simulation results of the warm forming process are compared with the corresponding cold forming results and advantages as well as disadvantages of warm forming are highlighted.

METHOD

A cup deep drawing example from literature is used for the validation of the simulation methods available in LS-Dyna. Van den Boogaard [9] provides a cup deep drawing geometry, material data for the drawn AA 5754-O aluminium sheet metal alloy as well as process parameters like tool temperatures, punch velocity, blank holder force and friction coefficients. The results for thickness distribution determined with the LS-Dyna simulation model are compared with the corresponding experimental and numerical results from van den Boogaard [9].

The following assumptions were made for the simulation with LS-Dyna: Temperature independent Young's modulus and Poisson's ratio, temperature independent thermal properties like heat capacity and heat conduction coefficient, constant heat transfer coefficient between blank and tooling (i.e. independent of gap distance and contact pressure), no heat transfer caused by convection or radiation, no conversion from plastic work to heat, constant friction coefficients, constant tool temperature and rigid tooling.

[1] Forming above the recrystallization temperature can have negative effects on the material properties caused by coarsening of grain structure and should therefore be avoided.

Van den Boogaard [9] describes the strain-rate and temperature dependent flow behaviour using two different models, the Bergstroem model and an extended Nadai model. In LS-Dyna measured flow curves for different temperatures can be defined directly in tabular form using material model 106 [12]. For temperatures lying between the defined ones, the corresponding flow curves are determined through linear interpolation. The strain-rate dependency is described with the Cowper-Symonds model [12]. This model determines the yield stress σ_y depending on the effective plastic strain ε_{eff}^p and the effective plastic strain rate $\dot{\varepsilon}_{eff}^p$ by scaling the quasistatic yield stress σ_y^s with the following equation:

$$\sigma_y\left(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p\right) = \sigma_y^s\left(\varepsilon_{eff}^p\right)\left[1 + \left(\frac{\dot{\varepsilon}_{eff}^p}{C}\right)^{\frac{1}{p}}\right]. \tag{1}$$

C and *p* are fit-parameters, determined for several temperatures. In order to validate the material definition, results of tension test simulations are compared with experimental results from literature.

Material model 106, which is used in this investigation, is an isotropic material model with v. Mises plasticity. Abedrabbo et al. [13] have developed a temperature dependent anisotropic material model for LS-Dyna. Unfortunately this model has so far not been implemented in the latest version.

The coupling of the mechanical and thermal models follows a sequential approach. The mechanical and the thermal part of the problem are solved independently using different solvers. The mechanical part uses a dynamic explicit solution scheme, whereas the thermal part uses an implicit conjugate gradient solver.

The bottleneck in computation time is the explicit mechanical time step Δt_{mech} which is limited by

$$\Delta t_{mech} \leq \frac{l}{c} \quad \text{with} \quad c = \sqrt{\frac{E}{\rho(1-\nu^2)}}. \tag{2}$$

l is the element length, *c* the sound velocity, *E* the Young's modulus, *ρ* the density and *ν* the Poisson's ratio. A common technique to speed up the simulation is the application of both mass and time scaling. The default approach for mass scaling is to prescribe the mechanical time step for the entire simulation. In order to meet the desired time step, the mass of elements with a time step lower than the prescribed one is artificially increased.

Time scaling is applied by an artificial increase of tool velocities. In cold forming simulation the strain-rate sensitivity, which is a time dependent material property, is usually neglected. That's why time scaling can be applied without any modification of the material model. In warm forming the material is dependent on temperature and strain-rate. Therefore all time dependent material and process parameters like strain-rate sensitivity, thermal conductivity and heat transfer coefficients have to be scaled according to the increase of tool velocity. Care must be taken when mass and time scaling are used extensively. Erroneous results can occur due to artificially appearing inertia forces [11].

As mentioned in the introduction, in the past, researchers often focused on the simulation of deep drawing examples with very small deformation rates. These examples have little relevance for industrial forming processes because the resulting cycle times are not applicable in serial production. For that reason the punch velocity of the validated LS-Dyna simulation model is increased to ten times of the original value. The results of the slow and the accelerated forming simulations are compared and the optimisation potential of the accelerated process is discussed.

RESULTS

At first the results of the tension test simulations with the material model set up for LS-Dyna are compared with the corresponding experimental results from literature. The tension test geometry is shown in Fig. 1.

In order to make the validation results comparable, the temperature and strain-rate dependent flow curves were determined using the Nadai model with the according model parameters from van den Boogaard [9].

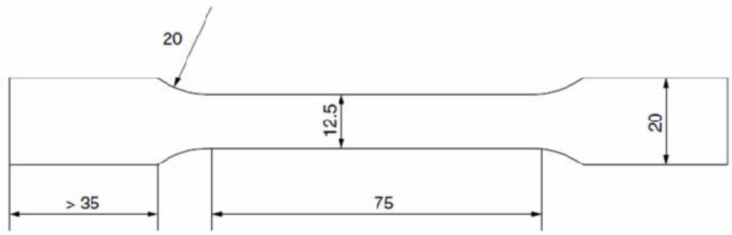


FIGURE 1. Geometry of the simulated tensile test specimen (dimensions in mm) [9]

TABLE 1. Temperature dependent Cowper Symonds strain-rate parameters

Temperature [°C]	***C*** **[s^{-1}]**	***p*** **[-]**
25	237300.00	3.030405
100	6419.4396	3.015913
175	156.11445	2.969855
250	3.0806286	2.826168

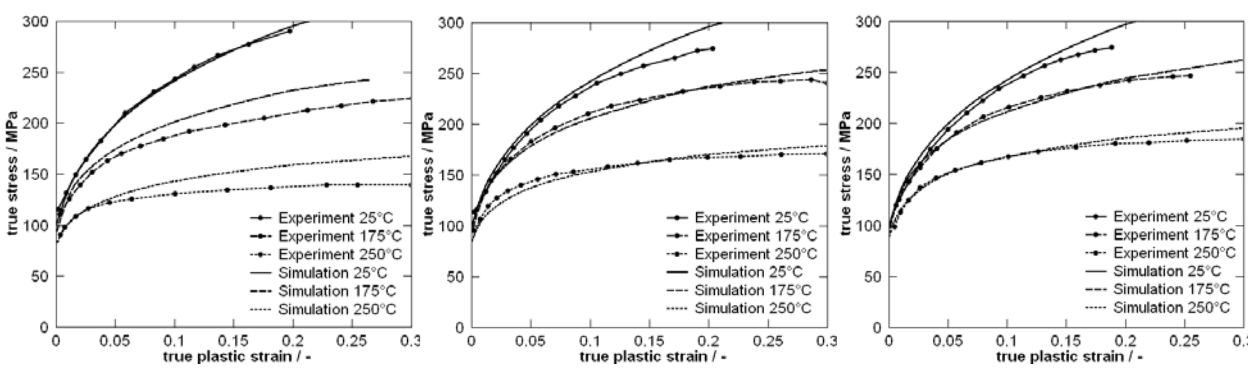
Flow curves for temperatures of 25, 100, 175 and 250 °C were defined in tabular form. The Cowper-Symonds strain rate parameters were fitted for these temperatures (Table 1). Additional mechanical and thermal material properties are given in Table 2. Reduced integration Belytschko-Tsay shell elements with three integration points over the thickness were used. The element size was approximately 1 mm.

As shown in Fig. 2, the material model set up for LS-Dyna can describe the temperature dependent material behaviour satisfactorily. For higher strain rates the experimental results are modelled quite well, for the lower strain rate the differences are larger. This is in accordance with the simulation results of van den Boogaard [9].

Based on the validated material data, a three-dimensional LS-Dyna deep drawing simulation model of the example given in literature is set up. The deep drawing geometry is shown in Fig. 3. The process parameters are given in Table 3. The punch is kept at room temperature whereas the die and the blank holder are heated up to 250 °C. Before deep drawing the blank is in contact with the die and the binder and is heated until the desired temperature is distributed homogeneously. Default deep drawing simulation settings, like reduced integration Belytschko-Tsay shell elements with three integration points over the thickness, a mesh size of approximately

TABLE 2. Mechanical and thermal material properties

Density	2700 kg/m³
Young's modulus	71000 N/mm²
Poisson's ratio	0.33
Sheet metal thickness	1.2 mm
Heat capacity [14]	900 J/kgK
Heat conduction [14]	120 W/mK
Thermal expansion coefficient [14]	$2.4 \cdot 10^{-5}\ K^{-1}$



(a) $\dot{\varepsilon} = 0.002\ s^{-1}$ (b) $\dot{\varepsilon} = 0.02\ s^{-1}$ (c) $\dot{\varepsilon} = 0.1\ s^{-1}$

FIGURE 2. Experimental and LS-Dyna simulation results of the uniaxial tension test

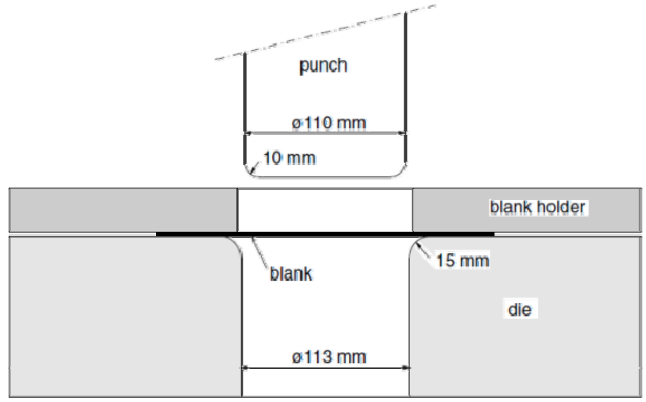


FIGURE 3. Geometry of the cup deep drawing example from literature [9]

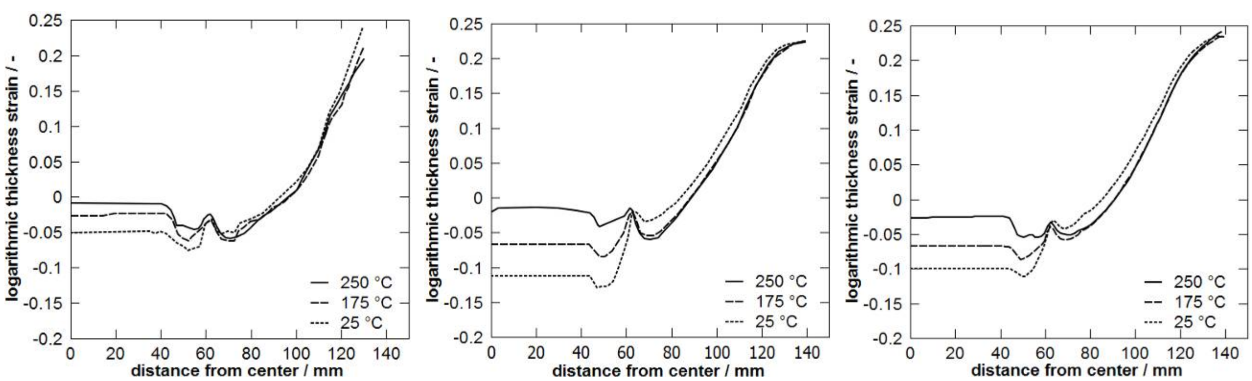
TABLE 3. Process parameters [9]

Drawing depth	80 mm
Drawing ratio	2.09
Punch velocity	2 mm/s
Blank holder pressure	1 N/mm²
Friction < 110 °C	0.06
Friction > 110 °C	0.12
Heat transfer coefficient [15]	1400 W/m²K

2.5 mm and a penalty contact algorithm were used. For symmetry reasons the simulation model represents only one quarter of the original geometry. The simulation time on a standard HP workstation with two CPU's was about 15 min. The determined results for thinning along the cross section are compared with the experimental and numerical results from literature.

Figure 4 shows the thickness distribution along the cross section after deep drawing with flange temperatures of 25, 175 and 250 °C. As it can be seen, the LS-Dyna simulation results are in quite good agreement with the simulation results of van den Boogaard [9]. Nevertheless, in comparison to the experimental results, both simulation models overestimate thinning especially in the cup bottom area.

As explained in the introduction, a punch velocity of 2 mm/s, which was used for the validation of the deep drawing simulation at elevated temperatures, is not applicable in serial production. Therefore the punch velocity is increased to 20 mm/s, which is still quite slow but more significant for industrial application.



(a) van den Boogaard experimental [9] (b) van den Boogaard simulation with Nadai model [9] (c) LS-Dyna simulation

FIGURE 4. Experimental and numerical determined thickness distributions

The thickness distribution results with increased punch velocity and a flange temperature of 250 °C were determined using the LS-Dyna simulation model and are shown in Fig. 5. Due to significant strain rate hardening at elevated temperatures, the resistance against deformation in the flange and therefore the drawing force increase with forming speed. As a result, thinning in the cup bottom area is more pronounced in comparison to smaller deformation rates.

Two possibilities to reduce thinning are highlighted. The first one is to avoid heating up the blank homogenously. By heating up the flange quickly within about 5 s, the temperature in the blank centre remains low. Therefore the strength is relatively high and thinning in the cup bottom can be reduced. The second possibility is to keep the drawing radius at a low temperature [16]. In this way the material is cooled before it is drawn into the cavity. The strength in the cup wall is increased and extensive thinning in this area can be avoided. Numerically determined temperature distributions with and without a cooled drawing radius are shown in Fig. 6.

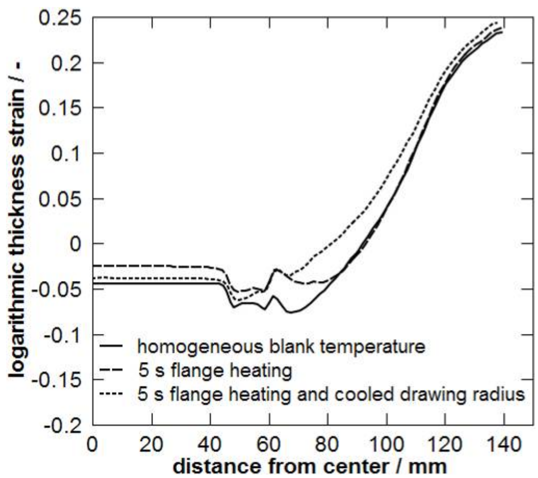


FIGURE 5. Thickness distribution results for different process layouts at 250 °C flange temperature and 20 mm/s punch velocity

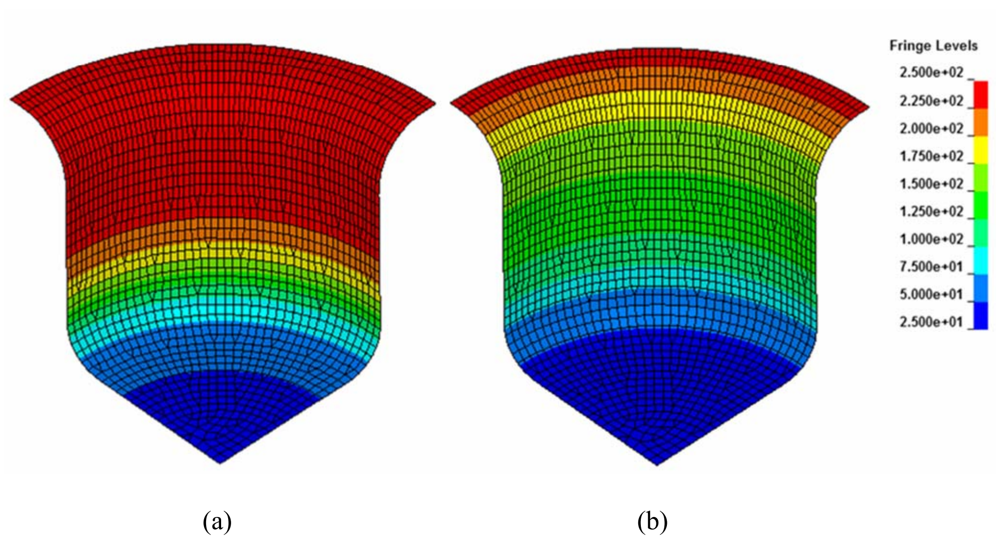


FIGURE 6. Numerically determined temperature distributions in °C after deep drawing at 250 °C flange temperature and 20 mm/s punch velocity (a) without and (b) with a cooled drawing radius

DISCUSSION

Experimental tension test data has to be used with care, because temperature increase due to plastic deformation was neglected. Correction methods for the determination of isothermal flow curves are not trivial to apply and isothermal testing in particular at higher strain rates is a demanding task. Additionally, extrapolation of tension test data is still an uncertain task to do, especially at elevated temperatures.

The deep drawing simulation results deviate from the experiments in particular at lower temperatures. The results can be improved by adapting the friction coefficients. So far friction has not been investigated in detail for warm forming of aluminium sheet metal and is therefore responsible for major uncertainty when simulation results are analysed. Furthermore a lubricant which is temperature resistant up to 300 °C and which can easily be removed in a press shop is so far not available off the shelf.

Anisotropy is a characteristic material property of aluminium sheet metal. Nevertheless it was neglected in this investigation. Van den Boogaard [9] considered measured R-values of about 0.72 by using an anisotropic Vegter yield function [17]. He showed that in the analyzed deep drawing example, the significance of anisotropy is quite small and is not responsible for the erroneous simulation results.

Experimental and simulation results proofed that thinning decreases with increasing flange temperature especially in the cup bottom area. This advantage diminishes with increasing forming speed due to significant strain rate hardening.

The evaluation of the feasibility of deep drawing geometries is usually not based on thinning results but on forming limit diagrams. For a reliable prediction of the feasibility of aluminium sheet metal warm forming processes, appropriate forming limit curves should be temperature and strain rate dependent. This recent field of research should be intensified in the future.

Assumptions that were made in this investigation, like constant tool temperature, constant heat transfer coefficient, no heat transfer caused by convection and neglecting the influence of deformation work to heat, are at least uncertain and have to be proofed in further research.

By heating only the flange area and keeping the drawing radius at room temperature the deep drawing results could be improved. It has been shown that exclusive heating of the flange area is easy to realise. This is not the case for cooling the drawing radius. So far there is no appropriate tooling technology available off the shelf which fulfils demands on thermal stability, mechanical strength and cost.

CONCLUSIONS

LS-Dyna can be used conveniently for the simulation of aluminium sheet metal deep drawing processes at elevated temperatures, although there is still the lack of a temperature dependent anisotropic material model.

Process parameters and their dependence on temperature, in particular the friction coefficients, have to be investigated and described for the process simulation of warm forming of aluminium sheet metal.

Increasing the tool velocity in warm forming of aluminium sheet metal is practical for industrial application, but has a negative influence on formability.

Optimised process strategies and advanced tailor made tooling technology can improve warm forming properties of aluminium sheet metal. Tailor made tooling for warm forming of complex geometries is a future field of research and engineering.

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