Simulation of Aluminium Sheet Metal Deep Drawing at Elevated Temperatures using LS-Dyna

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Abstract:

A disadvantage of aluminium is that it is less formable than steel. 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. 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 the process is optimized regarding formability and cycle time. The optimization focuses on the temperature distribution of the tooling and the blank, the punch velocity and the blank holder force.

Keywords:

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

1 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 methods like hydroforming or superplastic forming have been developed to improve the formability of aluminium sheet metal.
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 [1] 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 [2] 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 [3] proofed these observations for additional AlMg alloys. For more information Toros et al. [4] published a detailed review of the state of the art in warm forming of aluminium sheet metal.
The major disadvantage of warm forming of aluminium sheet metal 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 [5]. 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 [6]. 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.

2 Method

A cup deep drawing example from literature is used for the validation of the simulation methods available in LS-Dyna. Van den Boogaard [5] 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

[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.

distributions determined with the LS-Dyna simulation model are compared with the corresponding experimental and numerical results from van den Boogaard [5].
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.
Van den Boogaard [5] 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 [7]. 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 [7]. 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. [8] 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

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

l is the element length, *c* the sound velocity, *E* the Young's modulus, *ρ* the density and *v* 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 [6].
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. This accelerated process inheres disadvantages in formability. In order to overcome this disadvantages, optimized process strategies regarding the temperature distribution of the tooling, the heating of the blank and the blank holder pressure are introduced.

3 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 van den Boogaard[5].
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 [5]. 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.

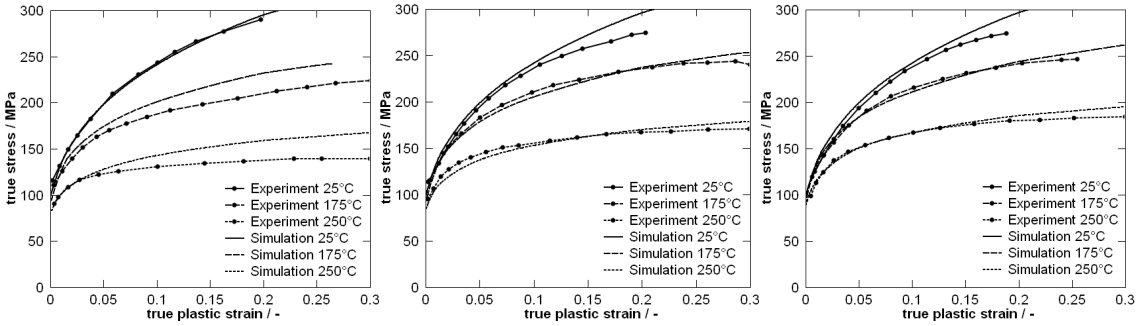
Table 1: Temperature dependent Cowper Symonds strain-rate parameters

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

As shown in Figure 1, 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 [5].
Based on the validated material data, a three-dimensional LS-Dyna deep drawing simulation model of an example given in literature is set up. The process parameters of the cylindrical cup deep drawing example 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 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 2 shows the thickness distribution along the cross section after deep drawing with flange temperatures of 25, 175 and 250 °C. As it can be se en, the LS-Dyna simulation results are in quite good agreement with the simulation results of [5]. 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.

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
Thermal expansion coefficient	$2.4 \cdot 10^{-5}$ 1/K
Heat capacity [9]	920 J/kgK
Heat conduction [9]	121 W/mK



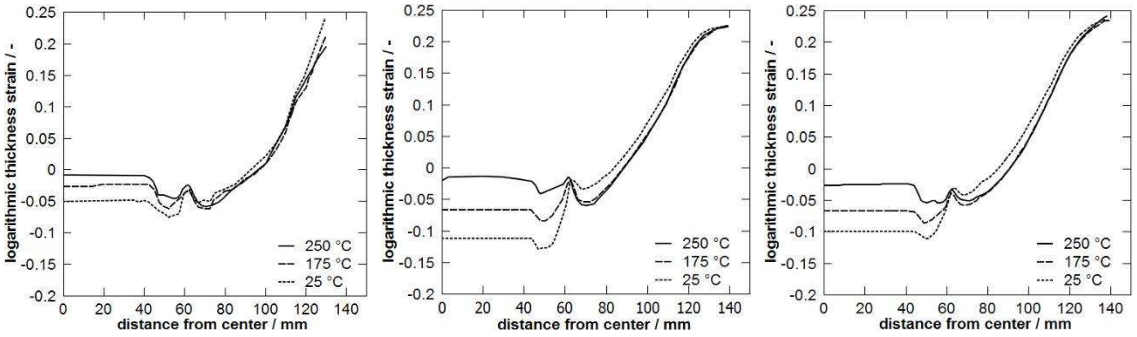
(a) $\dot{\varepsilon} = 0.002\ s^{-1}$ (b) $\dot{\varepsilon} = 0.02\ s^{-1}$ (c) $\dot{\varepsilon} = 0.1\ s^{-1}$

Figure 1: Experimental [5] and LS-Dyna simulation results of the uniaxial tension test

TABLE 3: Process parameters [5]

Drawing depth	80 mm
Punch diameter	110 mm
Die inner diameter	113 mm
Blank diameter	230 mm
Punch radius	10 mm
Die radius	15 mm
Punch velocity	2 mm/s
Blank holder pressure	1 N/mm²
Friction < 110 ℃	0.06
Friction > 110 ℃	0.12
Heat transfer coefficient [9]	1400 W/m²K

The thickness distribution results with increased punch velocity and a flange temperature of 250 ℃ were determined using the LS-Dyna simulation model and are shown in Figure 3. 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.



(a) Experimental[5] (b) Simulation with Nadai model [5] (c) LS-Dyna simulation

Figure 2: Experimentally and numerically determined thickness distributions

Two possibilities to reduce thinning are highlighted in Figure 3. 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 die radius at a low temperature [10]. 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.

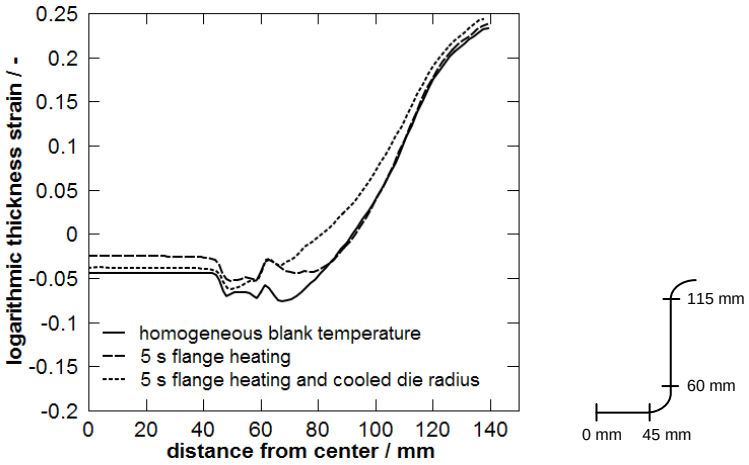
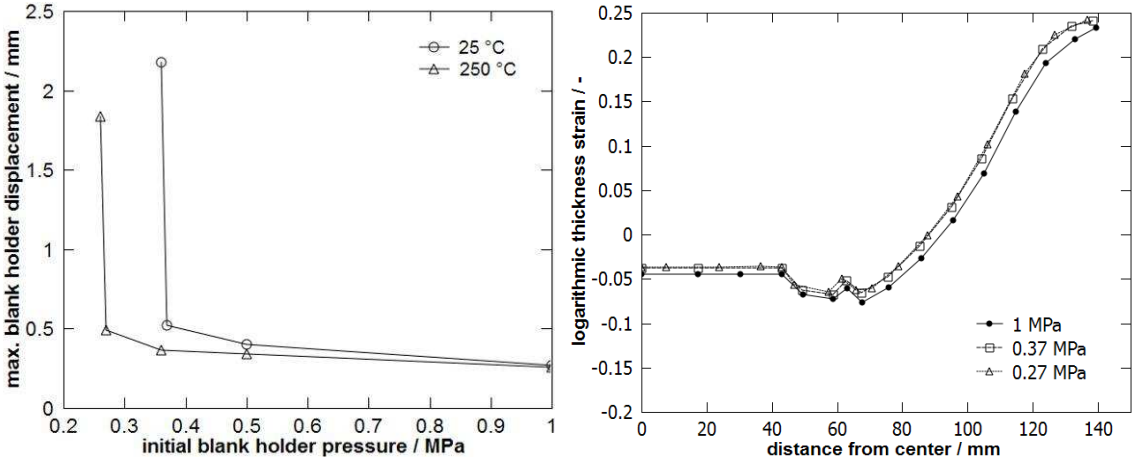


Figure 3: Thickness distribution results for different process layouts at 250 ℃ flange temperature an d 20 mm/s punch velocity

Another advantage of deep drawing at elevated temperatures is, that the wrinkling tendency in the flange area decreases with increasing temperature [11]. Therefore the binder force and hence the drawing force can be reduced in comparison to cold forming. As a result, thinning in the cup bottom and wall area decreases. In order to proof these statements a corresponding investigation using the validated LS-Dyna simulation model is presented. It has been shown that FEM simulations can be used to predict wrinkling in sheet metal deep drawing [12]. Nevertheless the obtained results should be treated cautiously because the onset of wrinkling and its mode are very sensitive to details of the analysis, like blank mesh and the FEM code used [13].
In the current investigation wrinkling has been detected by measuring the maximum blank holder displacement dependent on initial blank holder pressure. A significant jump in the displacement curve indicates that the minimum blank holder pressure has been reached. The minimum blank holder pressure at 25 ℃ flange temperature is 0.37, where as at 250 ℃ it is 0.27 MPa (see Figure 4a). As shown in Figure 4b, a decrease in thickness reduction can be reached by reducing the blank holder pressure from 1 MPa to the determined minimum values. Nevertheless there is almost no difference between the determined minimum values for 25 and 250 ℃.



(a) Maximum blankholder displacement dependent on initial blank holder pressure

(b) Thickness distribution results for the determined minimum blank holder pressure values at 250 ℃ flange temperature and 20 mm/s punch velocity

Figure 4: Minimum blankholder pressure and corresponding thickness distribution

4 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 [5] considered measured R-values of about 0.72 by using an anisotropic yield function [14]. He showed that in the analyzed deep drawing example, the significance of anisotropy is small and 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.
Furthermore it has been proofed that, in comparison to cold forming, lower blank holder pressure can be applied in warm forming. Nevertheless the difference of the determined minimum values for room temperature and for 250 °C flange temperature is negligible. Therefore the impact of lower blank holder pressure in warm forming on thinning could not been reproduced with FEM simulation in this investigation.

5 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.

6 Acknoledgements

The authors wish to thank the “COMET K2 Forschungsförderungs-Programm” of the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT), the Austrian Federal Ministry of Economy, Family and Youth (BMWFJ), Österreichische Forschungsförderungsgesellschaft mbH (FFG), Das Land Steiermark, and Steirische Wirtschaftsförderung (SFG) for their financial support. Additionally, we would like to thank the supporting companies and project partners SAG Alutech GmbH and weba Werkzeugbau Betriebs GmbH as well as the Institute for Materials Science and Welding/Graz University of Technology.

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