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On appropriate Finite Element discretization in simulation of gas-based hot sheet metal forming processes

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Abstract. Gaseous medium is being used for sheet metal forming at elevated temperatures, especially for lightweighting purposes. These processes enable forming of high strength alloys of a wide range of thickness due to low material flow stress as well as improved formability. In these processes, the resulting component properties are an interplay of numerous parameters. Instead of cost and time intensive experiments, FEM aids an effective and economic process optimization and enables a better understanding of the influence of process parameters on the component properties. In the current study, the importance of appropriate discretization of the workpiece within a gas-based hot sheet metal forming process is investigated based on a laboratory scale component. AA6010 sheet metal blanks of different thicknesses are studied numerically and experimentally. Simulations with different types of elements are performed and the evolution of process parameters as well as their influence on the final component thickness are analysed. Different element types resulted in noticeable difference in the simulation results and this difference also varies with the initial sheet thickness. Upon further experimental validation, the suitable element type for workpiece discretization is suggested, which enables practitioners to get reliable results via FE simulation of these processes.

1. Introduction
Since the mid-twentieth century, active media have been used to enable forming of sheet metal components that are too complex to be realized via conventional deep drawing processes. According to DIN8584, there are various active media based processes for forming the sheet metal. At high forming temperatures, gaseous media have been used for this purpose since 1960s, in the superplastic forming of Al-Zn Alloy, and later in 1970s for Ti-6Al-4V and Al-6Cu-0.5Zr alloys successfully [1]. These superplastic forming processes which employ a hot tool-setup are nearly isothermal and can be simulated accordingly. In recent times, several processes have been tested for forming high strength lightweight alloy sheets at higher forming speed in order to reduce the cycle time. An overview is given in [2, 3]. There are several variants of the rapid gas-based hot sheet metal forming, with cold or warm tools [4], with hot tools [5] and in some cases tools with integrated heat treatment facilities [3].

Regardless of these process-specific differences, the rapid gas-based forming processes require a coupled thermo-mechanical forming simulation as in hot stamping [6] due to prevailing transient thermo-mechanical conditions. Furthermore, in contrast to hot stamping, at least a part of the forming in these processes is realised by gas pressure. The associated gas flow results in a dynamic temperature field which consequently influences the material flow stress and therefore this must be considered in the simulation. Other aspects of FEM such as the spatial discretization of the workpiece and element formulation also influence the accuracy of the simulation results. Therefore it is important to understand
if the methods of discretization and element types used in conventional sheet metal forming processes still give reliable results under current process conditions. The aim of this work is to study different finite element discretization methods and to validate the simulation results with help of laboratory scale experiments.

2. State of the art of simulation of active media-based forming processes

In conventional punch-based hot sheet metal forming simulations, the sheet is generally modelled using thin shell elements [7] where the through-thickness temperature and stress gradients may not be accurately predicted [8]. Proceeding from this, shell elements are also being used in simulation of active media based hot forming process in some of the existing studies [9, 10] for thickness ranging from 1.5 to 2 mm yielding reasonable results. From [11] it can be seen that the shell elements with additional thickness stresses also did not result in much difference in terms of resulting thinning. However, due to the improved formability of the material in active media based forming, localized sheet thinning and subsequent multiaxial stress states occur, which cannot be modelled with the plane-stress shell elements effectively [12].

The shell elements cannot effectively reproduce the through-thickness normal stresses exerted by fluid pressure, which might sometimes exceed the in-plane stresses in active media based forming processes [13]. Shell elements were shown to be less effective than multi-layered solid elements in predicting the non-uniform deformation in thickness direction and resulting thinning at small corner radii in similar processes [14]. Therefore, solid elements were preferred for simulations [15]. Also, the stress and temperature gradients across the sheet thickness occurring in a non-isothermal hot forming process can be sufficiently captured by multi-layered solid elements [16]. Another characteristic of the rapid gas-based forming processes is that the high pressure gaseous medium cools-down the component significantly [17]. This is not always considered in FE simulations but important because of the temperature-dependence of the material flow stress and forming limits.

To summarize, shell elements work well for low sheet thickness to curvature ratio but cannot represent the non-uniform through-thickness stresses and resulting non-uniform deformation. Shell elements with thickness stretch also consider normal stresses in addition to in-plane stresses. Layered solid elements capture all effects and give better results in simulation of gas-based thick sheet forming. Thick shell elements, where the sheet is modelled with continuum 3D elements which are similar to those of thin shells, also consider non-uniform through-thickness effects. The applicability of an element type for a particular scenario mainly depends on the thickness of the sheet, geometrical features such as the die corner radius, the expected strains the sheet undergoes during the forming operation and the through-thickness stress and temperature variation.

2.1. Gaps in literature and Problem statement

So far, within process simulations, the influence of the used element type on the simulation results in terms of the sheet thickness is not clear. Although the capabilities of shell and solid elements were studied, in-depth investigations of the resulting temperature field, thinning evolution and thickness effects were not the main focus. Thermal boundary conditions and coupled thermo-mechanical simulation of the problem which was proven to be important, was sometimes not considered. Moreover, gas-based hot forming of thick sheets (> 2 mm) was not performed or simulated in the existing studies.

The current work aims to investigate the process with help of FEM and experiments of a laboratory scale component. FE simulations are performed to determine the suitable element type to predict reliable results. For this purpose, the resulting temperature field and thickness distribution within the component estimated by different element types are analysed. In-depth investigations with initial blank thickness ranging from 1.5 to 4 mm are carried out to understand how the discretization effects vary with varying thickness. Using experimental validations, the suitable methods of discretization for gas-based hot forming process for a blank of given initial thickness are finalized.
3. Materials and Methods

3.1. Material characterization for determination of flow curves
In the current process, circular blanks cut from A6010 T6 aluminium sheet are subjected to hot forming near the solution heat treatment temperature of 565 °C. For modelling the material plasticity in FEM, the flow stress under process conditions should be determined. Since the process typically involves very high strains, the uniaxial tensile test is not a viable option to determine flow curves for the investigated temperature range due to early necking of the specimen. Hence, isothermal stacked layer compression test which enables large height reduction is chosen. In Figure 1a, the stacked test specimen before and after the experiment for a height reduction of more than 50% is depicted. Here, minor frictional influence cannot be avoided because complete lubrication might result in slipping at the specimen-tool interface and consequently a separation of the individual layers. All specimens are initially solutionized at 565 °C, compressed at the test temperature and the recorded force-displacement data is used for obtaining the flow curve field in Figure 1b showing a high temperature and strain rate sensitivity. After reaching a maximum at a true strain of 0.05, the flow stress either remains constant or slightly decreases exhibiting ideally plastic to softening behaviour that is typical to this group of aluminium alloys [18].

3.2. Experimental setup and gas-based hot forming process
The current experimental setup is a modified version of Hot Gas Bulge Test [19] with a closed die and a blank holder, which are maintained at a constant temperature of 565 °C throughout the process by using an integrated heating unit along with appropriate insulation as in Figure 2a. A cross-sectional view is depicted in Figure 2b with the die depth, entry and bottom radii in mm. Circular blanks with a diameter of 150 mm and different thicknesses are used. Two repetitions are performed for each experiment.

During the process, the blank is placed in between the hot tools and it is heated up conductively until the temperature of tools is attained. After the blank undergoes solution heat treatment at this temperature for sufficient time, it is rapidly formed with high pressure gas while regulating the blank holder force as shown in the following Figure 3a. For all cases, the gas pressure increases linearly until 14 MPa in four seconds and remains constant after that. The blank holder force is around 15 kN at the process begin, increased gradually until 50 kN and remains constant after that. The variation of blank holder force with increasing pressure is typical in active media based forming processes [20] in order to compensate the increasing counter gas pressure exerted on blank holder and enable sufficient sealing.
3.3. **Calibration of heat transfer coefficient**

During the forming process, the blank cools down significantly via forced convection due to the expanding high pressure gas which is at lower temperature. For calibration purpose, a blank of thickness $t_C = 4$ mm with an embedded thermocouple is subjected to high pressure gas and the temperature evolution is continuously recorded. Figure 3b shows that the workpiece cools down by approximately 90 K in eight seconds. The measured temperature drop is reproduced in FE simulations and the forced convection coefficient is inversely determined to be approximately $300 \, \text{W/m}^2\text{K}$. This value is used for the simulations for modelling the temperature drop in the blank due to forced convection.

![Figure 3. (a) Variation of applied gas pressure and blank holder force during the process and (b) measurement of temperature drop for calibration of heat transfer coefficient](image)

3.4. **FE model setup and simulations**

Coupled thermomechanical process simulations are performed using the explicit solver of FE software package LS-Dyna version R9.0.1. Analog to the experimental setup, the simulation models consist of a die, blank holder and the workpiece as shown in the following Figure 4a. Only a quarter of the setup is modelled with help of symmetry boundary conditions. Due to ignorable elastic deformation of the tools under prevailing loads, they are modelled as rigid bodies made of tool steel X40CrMoV5-1 with physical properties from [21]. For blank, the physical properties are taken from [21] and the temperature and strain rate dependent flow curve field from Figure 1b is assigned using ‘Thermo_elasto_viscoplastic_creep’ material card 188. An average element size of 2 mm is used for discretization of the tools with relatively refined mesh at die entry and corner radii.

![Figure 4. (a) Cross-sectional view of FE model setup and (b) top view of discretized blank quarter](image)

3.5. **Boundary conditions and process parameters**

The tools and blank are assigned an initial temperature of 565 °C with thermal boundary conditions such as conduction, convection and radiation at corresponding interfaces. The interfacial contact is modelled according to Coulomb with a friction coefficient of 0.17 according to the used Boron nitride lubricant [22]. The gas pressure is applied as a uniform surface load on the blank as shown in Figure 4a. The die is fixed and the blank holder force as shown in Figure 4a is applied as a rigid body force.

3.6. **Modelling and discretization of the blank**

The element types shown in the following Table 1 are used in the current study for discretizing the workpiece. The number of integration points in the thickness direction $N_{IP}$ or/and the number of elements over the blank thickness $N_E$ as shown in Table 1 are used. To maintain a good aspect ratio, the in-plane solid element size is taken to be 0.5 mm for 1.5 mm thin blank and 2 mm for the thicker blanks.
Table 1. Different types of elements used for the discretization of the blank in this study [23]

| Element type | Simple shell | Thick shell | Solid |
|--------------|--------------|-------------|-------|
| Description  | \(\sigma_{xx}, \sigma_{yy}, \sigma_{zz} = 0\) | \(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}\) | \(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}\) |
| Formulation (In LS-Dyna) | Belytschko-Tsay (ELFORM 16) | Belytschko-Bindeman (ELFORM 5) | Constant stress S/R (ELFORM 2) |
| Thickness discretization | \(N_{ip} = 9\) | \(N_{E} = 5, N_{ip} = 9\) | \(N_{E} = 5\) |
| Shape | Quadrilateral | Hexahedron | Hexahedron |

The thermal discretization in case of shell elements is generally done by nodal extrapolation in thickness direction according to the used integration scheme. In solid elements the temperature is directly calculated at the nodes. Purely thermal calculations showed that all these different types of discretization resulted in the same rate of temperature drop within the blank due to convection.

4. Results and Discussion

4.1. Experimental results

The geometry of the formed components is scanned with a 3D surface measuring device (HandySCAN 700) in order to assess the form-filling. An instance of the formed component and the measured deviation from the desired geometry for different starting blank thicknesses \(t_0\) are shown in the Figures 5a and 5c respectively. For all three thicknesses with two repetitions, a complete form filling is achieved under the applied pressure with a maximum deviation less than 0.5 mm.

![Figure 5](image)

**Figure 5.** (a) Formed component with reference to initial blank, (b) cross-section and the thickness measuring points and (c) scanned geometries showing nearly complete form-filling

The local wall thickness of the components is measured along the diameter using a micrometer. The specimens are cut and the thickness is measured normal to the outer surface at equidistant measuring points with 5 mm gap along the X-axis as shown in Figure 5b. The measured thickness is used to calculate the relative thinning in %, which is shown in Figure 6 along with the simulation results. Furthermore, based on the final diameter of the components, the amount of sheet draw-in is calculated.

4.2. Simulation results

First of all the influence of element type on the simulated wall thickness distribution is analysed and compared with experimental results to see which of the element types gives a better prediction of experimental wall thickness distribution.
4.2.1. Influence of element type on the predicted wall thickness distribution

The experimental and simulated wall thickness distribution from centre towards the edge of the formed components is shown in Figure 6 in terms of relative thinning. In all experiments, the maximum thinning occurred near the corner radius of the component \((x \approx 40 \text{ mm})\). With an increasing initial blank thickness, the experimental thinning slightly decreases but the overall tendency is quite similar.

![Figure 6](https://example.com/figure6.png)

**Figure 6.** The wall thickness distribution from experiments and simulations with different elements

The corresponding simulations with different element types also show a similar tendency but significantly different amounts of wall thinning. This difference is noticeable in case of thin \((1.5 \text{ mm})\) and thick \((4 \text{ mm})\) sheet forming. Furthermore, for thin sheet forming, thin shell and solid elements seem to give a better prediction of the wall thickness distribution whereas for thick sheet forming, thick-shell and solid elements predict better compared to their counterparts. For the blank thickness in between, all element types resulted in a good prediction. In contrast to experimental observation, the shell elements result in inhomogeneous distribution and localised wall thinning when used for modelling \(4 \text{ mm}\) thick sheet, which shows their low capability to model thick sheets. The thick-shell elements predict the thinning well in case of thick sheets.

4.2.2. Influence of element type on predicted draw-in

Upon analysing the sheet draw-in according to Figure 5a, it can be seen from Table 2 that there is no significant difference when different element types are used for discretization of \(1.5\) and \(2 \text{ mm}\) thick sheets. However, the simulation of \(4 \text{ mm}\) thick sheet with shell elements showed a significant difference. This is because of the compressive deformation of sheet in flange region due to blank holder force which resulted in an outward material flow that partly compensated the net draw-in. This phenomenon in thick-sheets is captured by solid elements, but not the shell elements due to their incapability of reproducing the deformation under stresses perpendicular to surface.

| Table 2. Calculated draw-in (in mm) of the sheet at the edge based on initial and final shapes |
|---------------------------------|-----------------|-----------------|-----------------|
| Thickness \(t_0\) | \(t_0 = 1.5 \text{ mm}\) | \(t_0 = 2 \text{ mm}\) | \(t_0 = 4 \text{ mm}\) |
| Experimental | Shell | 5.5 | Shell | 5.5 | Shell | 2.5 |
| FE simulation | Shell | 6.8 | Solid | 5.1 | Thick-shell | 4.8 | Shell | 5.3 | Solid | 4.8 | Thick-shell | 4.6 | Shell | 8.9 | Solid | 2.1 | Thick-shell | 1.9 |

In order to further understand how different element types reproduce the evolution of wall thickness distribution, the process duration and the required pressure for complete form-filling are analysed. Since the temperature significantly influences the material flow, the evolution of temperature predicted by different element types during the forming process is also studied.

4.2.3. Influence of element type on the pressure required for form-filling

As the process duration is very short, it is difficult to identify the instance of complete form-filling in real process exactly. However, it can be seen that the simulations with different element types also predict this differently. In all cases the corner radius is formed towards the end of the process and the pressure at this instance is determined. As shown in Figure 7, the required pressure increases with
increasing initial blank thickness, which is obvious from the membrane theory. In all cases, the shell elements exhibit complete form-filling at relatively lower pressure and the solid elements require higher pressure which might be due to different stiffness exhibited by the element types. This also means that the process time until complete form-filling is longer in case of solid elements compared to the shell elements. The thick-shell elements tend to predict a pressure in between. This could be further validated by stopping the experiments at these instances and analysing the component.

**Figure 7.** The pressure (MPa) required for complete form-filling predicted by different element types for blanks of different initial thickness

4.2.4. **Influence of element type on evolution of blank temperature**

Due to the difference in process duration predicted by different element types, the blank also cools down by different amounts. Here, the variation of the temperature of blank at the corner radius for both the workpiece surfaces in Figure 8a is analysed and depicted in the Figure 8b. Significant difference is observed for the same applied thermal boundary conditions. It can be seen that the blank temperature first decreases via the forced convection due to gas and increases again during form filling due to thermal contact conductance because a continuously increasing contact with the die is established. Generally, the cooling rate is higher in case of thin 1.5 mm blank. The amount of temperature drop in a thin blank also significantly differs based on the used element type, whereas for the thick blank, it is not very significant. The through-thickness temperature difference between upper and lower surfaces also increases with an increasing blank thickness and is better reproduced by thick-shell and solid elements compared to the shell elements, where the curves for both surfaces are almost overlapping.

**Figure 8.** (a) Temperature measuring points and (b) evolution of temperature of workpiece at the corner radius for the surfaces exposed to gas and towards the die

As mentioned earlier, based on a purely thermal simulation, all these elements are equally capable of modelling the temperature drop due to convection. This can also be seen by the rate of temperature drop in the beginning which is equal for all the elements for a specific blank thickness. However, during the process, the temperature evolves differently, which might be due to different rate of form filling and contact establishment between deforming blank and die. This further leads to a different local material flow behaviour due to the high temperature and strain rate dependence of the material. The resulting evolution of thickness in turn influences temperature in a complex manner. For example, highly thinned regions lead to high temperature loss as long as there is no contact and also get heated up faster as soon
as the contact is established. Further investigations with experimental temperature measurement are necessary to see which of the above elements predict the temperature evolution exactly.

5. Conclusion and Scope
In the current study, FE simulations of gas based forming of a laboratory scale component are performed with different element types and the simulation results and the experimental results are comparatively analysed. Within the process, the same gas pressure profile and boundary conditions are applied to form blanks of different initial thicknesses. It can be seen that both the shell and solid elements give reliable prediction of wall thickness distribution for forming 1.5 mm thick blank whereas solid elements give better prediction in case of 4 mm thick blank forming. It is mainly because the gas pressure required for the complete form-filling and the corresponding process duration are predicted differently by different element types. Consequently, the resulting temperature field as well as the through thickness temperature effects varied significantly. Thus, in order to reliably use FEM for process layout of a specific component with focus on the component wall thickness distribution, a verified element type according to the initial blank thickness should be used.

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