Multi-objective sheet metal forming simulations using a software agnostic platform

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Abstract. The development of new technologies for forming lightweight sheet metals into vehicle components has resulted in a rapid growth of advanced predictive models to analyze such processes. Simulations of the warm and hot forming of aluminium alloys in particular have been conducted on numerous finite element (FE) software packages with various specific phenomena being captured through the implementation of subroutines, to ensure that parts formed are free of defects and meet the required post-form strength. However, access to such models is lacking, with each having to be adapted to the software being used, and are computationally expensive to run, limiting the capabilities of simulations and increasing the challenges of utilizing new forming technologies effectively. Smart Forming is a knowledge-based cloud platform that was developed to overcome these challenges. It is composed of functional modules based on predictive models made accessible on the cloud that can be run individually or simultaneously. A conventional forming simulation is first run locally in any FE software of choice, and the required results uploaded to the modules on the platform for remote computation to investigate the phenomena of interest. In this work, simulation data from two different software packages, PAM-STAMP and Autoform, were processed for the same U-shaped component in the Smart Forming modules ‘Formability’ and ‘Tailor’, to demonstrate the multi-objective simulation and software agnostic capabilities of the platform.

1. Introduction

The growing demand for lightweight materials to improve vehicle efficiencies, and the development of new technologies to form them successfully, has necessitated extensive developments in finite element (FE) simulations for determining optimal forming process parameters. Warm and hot stamping of 6xxx and 7xxx series aluminum alloys in particular, which are of greatest interest to the automotive industry, require careful selection of such parameters to achieve a final component with the desired qualities such as the absence of necking and a high post-form strength [1].

Conventional FE simulation software packages such as PAM-STAMP and Autoform are traditionally used to model forming processes, however a comprehensive representation and analysis of the process can only be realized through the incorporation of advanced predictive models. Such models have been developed previously for predicting necking at high temperature conditions [2,3] as well as post-form strength [4-6]. However, they have typically only been implemented as subroutines [7-9], which require significant computational knowledge of specific FE software, are computationally expensive to run, and can only be run individually.
Smart Forming was therefore developed as a knowledge-based platform available on the cloud that enhances the capability of FE simulation software [10]. Multiple functional modules built from theoretical models, both virtual and physical, enable different features of forming processes to be predicted and analyzed. Unlike subroutines, the modules do not have to be developed for specific FE software and do not have to be run locally in conjunction with FE simulations. Rather, they are compatible with multiple FE software packages and can be run on the cloud simultaneously. The modules currently available are shown in Figure 1, and include ‘Formability’ for necking prediction, ‘Tailor’ for post-form strength prediction, as well physical modules such as ‘IHTC-Mate’ for determining the interfacial heat transfer coefficient in a forming process.

![Figure 1. The Smart Forming simulation platform.](image)

In this work, the multi-objective capability of Smart Forming is demonstrated through the simulation of a U-shape component forming process. The two functional modules ‘Formability’ and ‘Tailor’ are used with two FE software packages, PAM-STAMP and Autoform, highlighting Smart Forming’s major advantage as a software agnostic platform. The setup of the FE models is first outlined, as well as the operating procedure of Smart Forming, followed by the results of the experimental verification and the individual modules, and finally a summary of the work conducted.

2. Methodology

2.1. FE model setup
FE models were developed in both PAM-STAMP and Autoform for the U-shape component forming process, as shown in Figure 2. The process parameters utilized were based on experimental trials conducted with a dedicated forming toolset and press in the lab, and are shown in Table 1. Namely, a blank with dimensions of 290 x 86 x 1.5 mm³, with the longitudinal dimension aligned with the rolling direction, was formed at a temperature of 490°C and speed of 250 mm/s into a U-shape component with a depth of 50 mm, the results of which were also used to verify the FE simulation results. Springback was not investigated as part of this work, but rather the thickness, level of necking and post-form strength of the formed component were analyzed.

The FE model setup for both software packages was identical, except that a symmetry plane was utilized in PAM-STAMP and only half the component was simulated, whilst the full component was simulated in Autoform. The material assigned to the blank was a temperature and strain rate dependent look-up table, based on the results of uniaxial tension tests on 1.5 mm thick AA6082 at temperatures of 300 to 500°C and at strain rates of 0.1 to 10/s, conducted on a Gleeble 3800 thermo-mechanical simulator. The tool geometry was based on the dimensions of the die, punch and blankholder of the
experimental forming toolset, and a default tool material from each FE software was assigned to the different tool parts.

| Parameter                      | Value          |
|--------------------------------|----------------|
| Initial workpiece temperature (°C) | 490            |
| Initial tooling temperature (°C)   | 20             |
| Punch speed (mm/s)               | 250            |
| Blankholding force (kN)          | 5              |
| Friction coefficient             | 0.15           |
| Heat transfer (mW/mm²K)          | Function of pressure/gap |

2.2. Smart Forming setup
Smart Forming functional modules are accessible on www.smartforming.com, and for this work the two modules utilized were ‘Formability’ and ‘Tailor’. The objective of using these modules was to determine the level of necking and the post-form strength of the component at the selected forming process parameters. Current FE software packages do not have the capability to predict the effect of varying
temperature, strain rate and strain path on the level of necking, or on the post-form strength of a component. Both of these capabilities can be realized through the ‘Formability’ and ‘Tailor’ modules respectively, without requiring any modification to apply them to specific FE software. Whilst these modules have been previously applied to more complex-shaped geometries simulated in PAM-STAMP, a U-shape geometry was selected for this work to demonstrate Smart Forming’s multi-objective capability and its compatibility with Autoform, and potentially any FE software package.

To utilize the modules, FE simulations of the forming process were first run in PAM-STAMP and Autoform locally, and verified with the results of the experimental forming trials. Element data from each simulation, at regular time intervals from the start to the end of the process, was then exported and uploaded onto the Smart Forming platform. Each module requires specific element data as inputs for its inherent model to be computed, such as the strain and temperature history, and are shown in Table 2. The artificial ageing (AA) time and temperature, as well as the paint bake cycle, are set by the user manually.

With the relevant element data uploaded and information entered, each module was processed simultaneously on the cloud as a multi-objective simulation to determine the level of necking and post-form strength of the component. Once complete, the results of the computations could be downloaded and visualized in the respective FE software packages for analysis, or on the cloud platform itself as shown in Figures 5 and 6.

| Table 2. Required Smart Forming inputs. |
|----------------------------------------|
| Formability                            | Tailor                                |
| Blank material                         | Blank material                        |
| Stamping speed                         | Element temperature                   |
| Stroke                                 | Element major strain                  |
| Element temperature                    | Element minor strain                  |
| Element major strain                   | AA time and temperature               |
| Element minor strain                   | Paint bake cycle                      |

3. Results

3.1. FE model verification
The successful utilization of modules on the Smart Forming platform requires that the results of FE models are first verified with experimental results such as measured thickness or temperature distributions. The comparison between the experimentally measured [11] and simulated thickness distributions from PAM-STAMP and Autoform is shown in Figure 3. Figure 4 also shows the true membrane major strain contours for the formed components visualized in PAM-STAMP and Autoform. The good agreement between all three sets of data enabled the simulation results to be processed further in Smart Forming in order to assess the level of necking and post-form strength of the formed component, the results for which were not available in either simulation software package.
3.2. Formability

The objective of using the ‘Formability’ module was to assess the level of necking in the formed component for the selected process parameters, taking into consideration the temperature, strain rate and strain path variations that the material experiences. The module utilizes a Viscoplastic-Hosford-Marciniak-Kuczynski model to accurately predict where and when necking (and hence failure) would occur during a sheet metal forming process [3]. The results of applying the ‘Formability’ module to the U-shape component forming process are shown visualized in Smart Forming in Figure 5. For both the PAM-STAMP and Autoform simulations, the maximum value of the necking criterion was 1.4, which

Figure 3. Experimental and simulated thickness comparison.

Figure 4. True membrane major strain contours of the formed component visualized in (a) PAM-STAMP and (b) Autoform.
was well below the value of 10 which indicates necking. This agreed well with the experimentally formed component on which no necking or failure was observed.

The artifacts visible in the Autoform results occur due to the transformation of the nodal coordinates of the triangular elements of the blank into a matrix that could be plotted as a 3D surface in the Smart Forming computing environment, which is currently being improved by determining the element coordinate data and by developing more accurate plotting techniques.

For both simulations, the maxima occurred on the side wall of the component, although their exact locations may have differed due to the coordinate transformation utilized for the visualization of the results. This would be improved by implementing direct visualization of the results in the respective FE software packages, such as in Figure 4.

![Figure 5](image)

**Figure 5.** (a) Experimentally formed component, (b) PAM-STAMP ‘Formability’ results and (c) Autoform ‘Formability’ results.

### 3.3. Tailor

The objective of using the ‘Tailor’ module was to determine the post-form strength of the entire formed component, taking into account the entire deformation history of the component as well as user-input post-forming treatments. ‘Tailor’ enables a processing window to be developed for a forming process, accounting for different stages (heating, forming, ageing) and certain fixed parameters in a forming facility (e.g. environmental conditions) to achieve the target component strength for a given material and component design. The processing window is optimised by taking into consideration pre-existing precipitates and dislocations during hot stamping, as well as multi-stage post-form heat treatments, in an advanced post-form strength prediction model [6]. The results of applying ‘Tailor’ to the U-shape component forming process are shown visualized in Smart Forming in Figure 6, where the final Vickers
hardness values (HV) are presented for the determined optimal artificial ageing time and temperature of 4 hours and 180°C respectively.

![Hardness Contours](image)

**Figure 6.** (a) PAM-STAMP ‘Tailor’ results and (b) Autoform ‘Tailor’ results.

The hardness contours for the PAM-STAMP and Autoform simulations are almost identical, with only a slight discrepancy at the bottom of the component due to minor differences in the final temperature distribution from both simulations, which would be improved by exactly matching their heat transfer characteristics and tool material thermal properties. Figure 7 also shows the good agreement with the experimental hardness measurements, with the maximum strengths being observed in the central cavity and side wall of the component, and minimum strength in the blankholding region.

4. **Summary**

The multi-objective and software agnostic capability of the knowledge-based cloud platform Smart Forming was successfully demonstrated by applying it to the FE software packages PAM-STAMP and Autoform to analyse the level of necking and post-form strength of the formed component at the selected forming process parameters. While these features were not available for analysis in the FE software packages alone, the ‘Formability’ and ‘Tailor’ modules enabled these two objectives to be met, without requiring any modification to adapt the modules to specific software. The two functional modules selected could also be processed simultaneously on the cloud, rather than running each as a subroutine in conjunction with the FE simulation. Following this initial investigation, the platform will now be applied to the simulation of more complex-shaped components, with a greater variety of advanced predictive models. Further work will also be conducted to streamline the operating procedures related to exporting from and visualising the results in each FE software, as well as exploring the performance of Smart Forming with other software.
Figure 7. Experimental and simulated hardness results.

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