Simulation of Warm Forming of 5754 Sheet Aluminium

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1 Introduction

In November 2009 a project was set up to implement an innovative metal forming process into the automotive industry with the goal of producing lightweight, high accuracy, complex-shaped automotive aluminium panels using one main forming operation. The project was known as WAFT – Warm Aluminium Forming Technology – and was part-funded by the UK Technology Strategy Board. The opening premise was that increased formability could be achieved with existing aluminium grades when heated to temperatures in the range 200°C to 350°C [1]. At these temperatures the material does not undergo re-crystallization or achieve superplasticity yet still exhibits increased formability – but the optimum settings for blank and tool temperatures, and also forming rate, were not known. The project aim was to industrialise the warm forming concept to align with conventional cold processing in order to develop a manufacturing process that could achieve steel formability with aluminium. This was to be confirmed in an industrial cell running a demonstrator tool, at rates optimised for premium vehicle production.

The grade of aluminium chosen for the study was 5754; this is widely used for cold forming automotive body-in-white structural panels, and issues regarding assembly and behaviour in the vehicle are well understood. However, the reduced formability of 5754 compared with steel drives body-in-white design to adopt simpler forms and more numerous parts in sub-assemblies to create the required levels of complexity – all of which has significant cost implications and an impact on the overall carbon footprint of the manufacturing process.

2 Simulation Objectives

In order to apply the WAFT process on an industrial scale, Jaguar Land Rover requires a simulation tool for use during product development so simulation was a key part of the project. Moreover, simulation was also required to support tool design for the industrial demonstrator cell. However, successful implementation of simulation for warm forming requires consideration of parameters not usually considered for cold stamping – i.e., temperature dependent material properties, heat transfer between tool and blank, and also strain rate sensitivity.

Forming feasibility has for many years relied upon use of a forming limit diagram (FLD) to determine if a part can be safely formed. This empirical method has proved extremely useful – though it does have some limitations, notably the assumption that all regions of the blank have similar characteristics even when formed under different conditions (e.g., non-linear strain paths). The limitation of the FLD is exacerbated in warm forming; when the material is heated its formability changes depending on temperature. Moreover, warm aluminium shows increased sensitivity to strain rate. Hence, the stress-strain relationship and other material characteristics can no longer be assumed to be constant; and the FLD (based on tests conducted at a fixed temperature and strain rate) can no longer be relied on to determine if a panel will fail.

In order to deal with the increased complexity a two stage strategy was adopted. The first approach was to use an existing model already available in LS-DYNA ®, making any simplifying assumptions as necessary – i.e., isothermal conditions and a fixed strain rate. The second approach was to develop a new material model that not only included sensitivity to temperate and strain rate but also included a damage criterion to allow assessment of formability under all possible process conditions; this is henceforth referred to as the continuum damage mechanics (CDM) model.

3 Material Testing

Test-pieces were produced from commercial alloy 5754 supplied by Novelis UK Ltd in the form of 400 x 400 x 1.5mm sheet, in H111 condition. Two sets of experimental data were used, both to populate the existing model and to calibrate the continuum viscoplastic damage model: stress-strain data from isothermal uniaxial tensile tests and FLD data from isothermal cup forming tests.

Firstly, tensile tests were conducted under cold and warm forming temperatures, ranging from 20 to 300°C, and at strain rates ranging from 0.001 to $10s^{-1}$. The tests were conducted within a furnace and the strain fields were obtained by means of a non-contacting optical deformation measuring system (ARAMIS). Secondly, the FLD tests were carried out at various temperatures up to a maximum of 300°C, and forming speeds ranging from 5 – $300mms^{-1}$. The ARGUS system was employed for measuring surface strain based on pre-applied grid patterns, and for determining limit strains according to ISO 12004-2:2008.

4 Simulation Methods

4.1 Simulation Using Existing Model

In order to demonstrate an industrial scale production capability, a single-action tool was designed for forming a panel incorporating a number of features noted in automotive body-in-white. The panel included a number of steps and corners of different plan radii (Figure 1). Forming simulation was used to evaluate the details of the design; this was done early in the material characterization phase of the project before the CDM model had been developed so an existing LS-DYNA material models was used. The objective was to design a panel that was (a) formable in cold mild steel in terms of splitting, thinning and wrinkling, (b) not formable in aluminium at room temperature and yet (c) potentially formable in aluminium using a warm forming process.

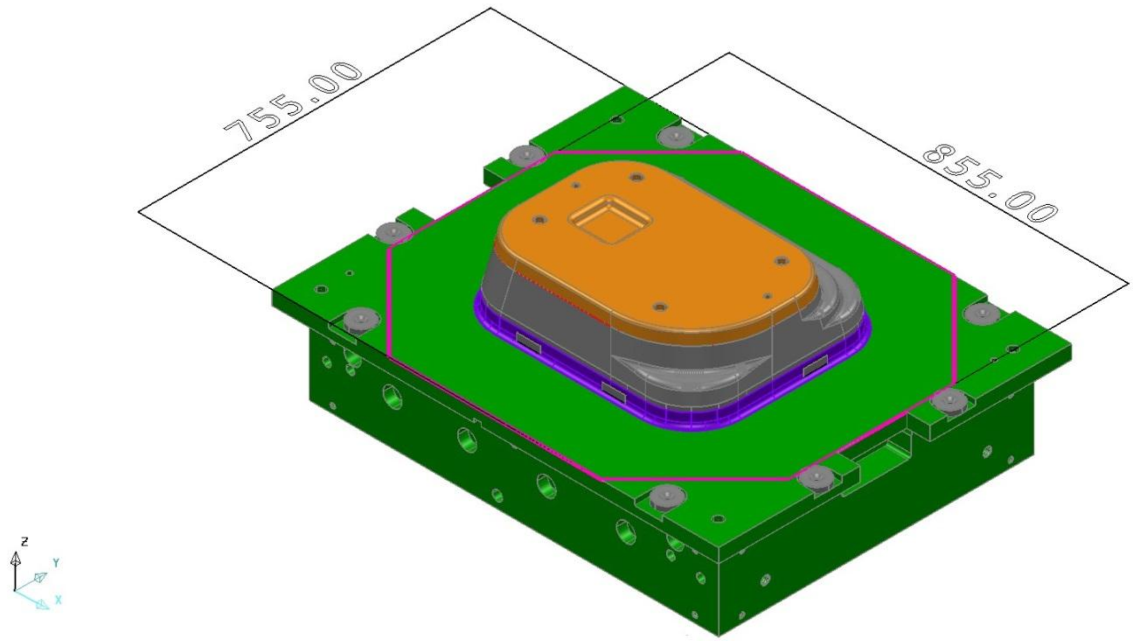

Figure 1: Demonstrator Tool Design for WAFT Project

The material model typically used for simulating the forming of aluminium sheet is *MAT_036, based on the Barlat & Lian yield surface [3]. This model accounts for the anisotropy in the plane of the sheet using the Lankford Coefficients (r00, r45 & r90). In addition to the r values (and the elastic properties), the model requires only a stress-strain curve (as a minimum). The results are then assessed for failure using a FLD (based on fixed settings of temperature and strain rate).

*MAT_036 was used to simulate all cases (cold steel and aluminium and three cases of warm aluminium at 200°C, 250°C and 300°C) with data from the material characterization tests. For the warm cases, the initial approach was to assume a constant strain rate with a stress-strain curve from test at that rate and temperature. There was no consideration of heat transfer in the analysis.

Towards the end of the project, sufficient data was available from material test and also from analysis of the press motion to allow use of the more advanced options in *MAT_036 to include a table of stress-strain curves over a range of strain rates, in combination with an upper die velocity profile taken from real time measurements. Mass scaling was applied to keep the analysis run times practical (the validity of the results was confirmed by checking against a run with no mass scaling applied). However, the problem of predicting failure when both temperature and strain rate are varying still remained – the FLD cannot be relied upon in such cases, hence the need for the CDM model.

4.2 Development of a New Material Model

To deal with the challenge of predicting failure, a new material model for 5754 has been developed and calibrated from experimental data (uniaxial tensile and FLD tests at 20 to 300°C, and at strain rates 0.001 to 10s-1). In a manner similar to that for creep deformation, general multi-axial power law viscoplastic equations can be obtained by considering a dissipation potential function [4-7]. With initial yield stress k, a set of multi-axial viscoplastic constitutive equations, incorporating damage evolution, may be written as:

$$\dot{\varepsilon}_e^p = \left(\frac{\sigma_e / (1-\omega) - R - k}{K} \right)^n \tag{1}$$

$$\dot{\varepsilon}_{ij}^p = \frac{3}{2} \frac{S_{ij}}{\sigma_e} \dot{\varepsilon}_e^p \tag{2}$$

$$\dot{R} = 0.5 B \bar{\rho}^{-0.5} \dot{\bar{\rho}} \tag{3}$$

$$\dot{\bar{\rho}} = A(1-\bar{\rho}) \dot{\varepsilon}_e^p - C \bar{\rho}^{n_2} \tag{4}$$

$$\sigma_{ij} = (1-\omega) D_{ijkl} \left(\varepsilon_{ij} - \varepsilon_{ij}^p \right) \tag{5}$$

$$\dot{\omega} = \frac{\Delta}{(\alpha_1 + \alpha_2 + \alpha_3)^{\varphi}} \left\langle \frac{\alpha_1 \sigma_I + 3\alpha_2 \sigma_H + \alpha_3 \sigma_e}{\sigma_e} \right\rangle^{\varphi} \frac{\eta_1}{(1-\omega)^{\eta_2}} \left(\dot{\varepsilon}_e^p \right)^{\eta_3} \tag{6}$$

where $\dot{\varepsilon}_e^p$ in Equation (1) is the effective plastic strain rate formulated using the traditional power law (with effective stress σ_e and material constants K and n), and is also dependent on isotropic hardening R and the damage state variable ω. Equation (2) defines the plastic strain tensor in terms of the deviatoric stress tensor S_{ij}, effective stress and effective plastic strain rate. The evolution of material hardening, R, given by Equation (3), is a function of the normalised dislocation density, defined as:

$$\bar{\rho} = (\rho - \rho_i) / \rho_m \tag{7}$$

where ρ_i is the dislocation density for the virgin material (initial state), and ρ_m the maximum (saturated) value for the material. Thus ρ varies from ρ_i to ρ_m, and $\bar{\rho}$ varies from 0 (initial) to 1 (saturated) on the condition that $\rho_i \ll \rho_m$ [7]. The quantity D_{ijkl} in Equation (5) is the fourth order tensor of elastic constants, or the elastic matrix of the material.

The multi-axial damage is determined in Equation (6); α_1, α_2, α_3 are weighting factors controlling the influence of principal stress, hydrostatic stress and effective stress on failure. The exponent φ controls the effect of the multi-axial stress values on damage evolution and affects the shape of the FLC. Δ is a correction factor relating to the FLC test method (Marciniak or Nakazima).

The material constants k, K and n are temperature dependent, as are all the other parameters introduced in the equations (B, A, C, η_1, η_2, η_3) except n_2. The viscoplastic damage constitutive equations are a set of non-linear ordinary differential equations and cannot be solved analytically, so a numerical integration method is used [8]. The determination of material constants in constitutive equations is no easy task [see e.g., 9-11]. In this research, an evolutionary algorithm (EA-based) optimization method detailed by Li et al. [10] and Cao and Lin [11], is used.

Calibration of the CDM model is achieved using test data for different temperature and strain rates. Figure 2 shows the fitting results for the computed uniaxial viscoplastic damage part, showing good agreement between computed and experimental isothermal tensile test data. Calibration of the multi-axial part of the CDM model is then carried out using FLD tests; fitting results for computed (solid curve) and experimental FLDs (symbols) are shown in Figure 3.

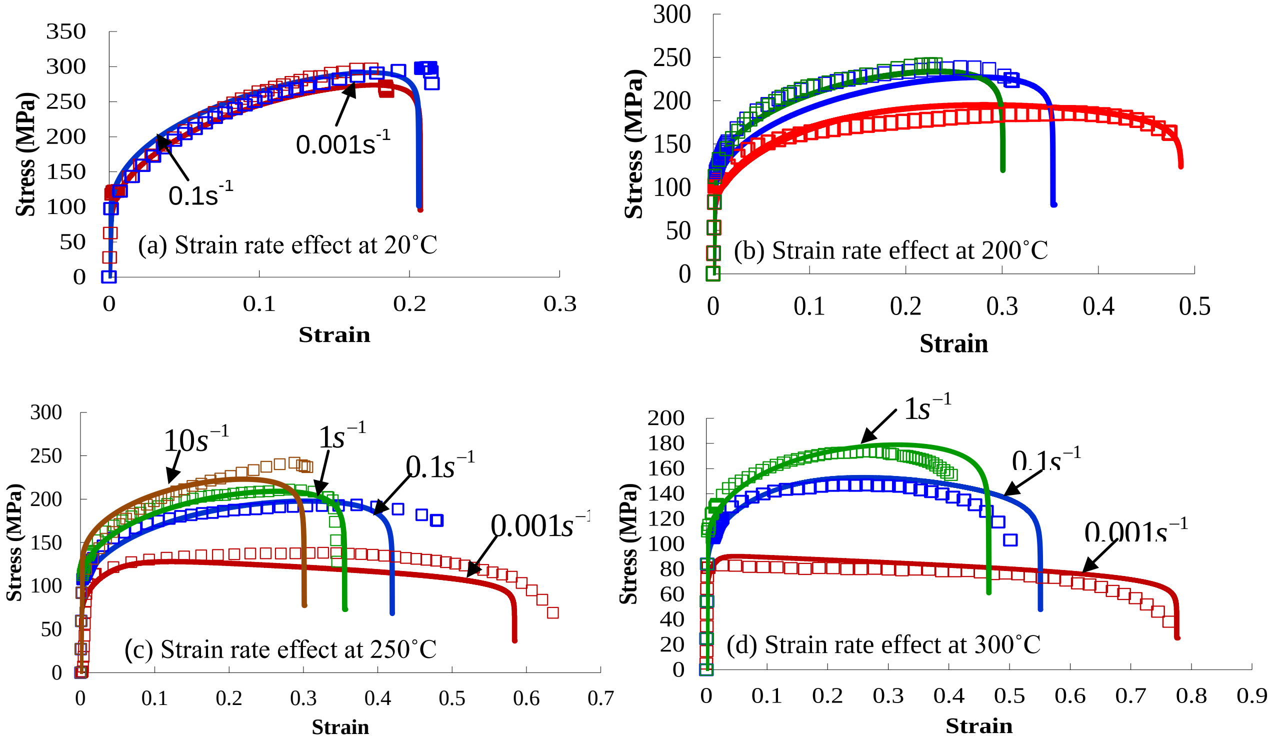

Figure 2: Comparison of experimental (symbols) and computed (solid curves) stress-strain relationships for different temperatures and strain rates.

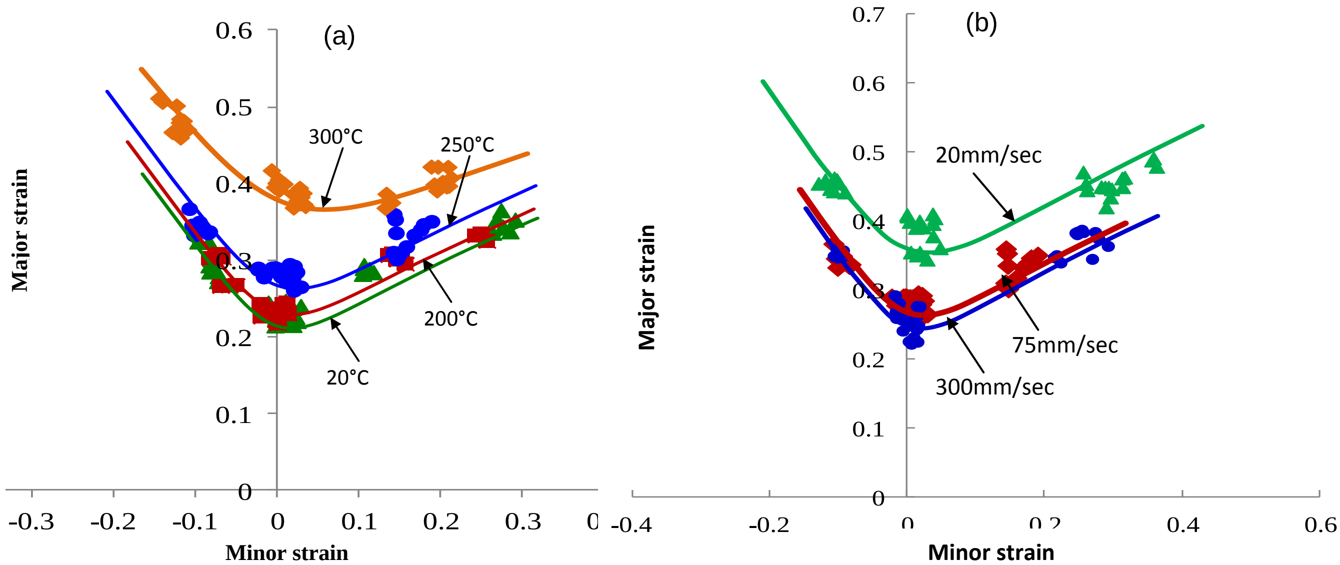

Figure 3: Comparison of experimental (symbols) and computed (solid curves) FLDs for (a) different temperatures at a forming rate of 75mms-1 and (b) different forming rates at 250°C.

5 Demonstrator Tool Trials

The final stage of the project was to run the demonstrator tool in an industrial cell to provide proof of concept for the warm forming process. The tool design developed with the help of the simulation model was built and installed in a press (Figure 4). The image shows the tooling enclosed in insulation material to prevent heat loss; the cabling shown is for the cartridge heaters used to heat the tooling, as well as the thermocouples to measure and control the heating.

Figure 4: Demonstrator Tool installed in Press for Trials

Initial panels were produced using this tool with blanks of both steel and aluminium at room temperature to test the design and the predictions of the LS-DYNA *MAT_036 model. An unexpected development arose when the first panels were found to have more formability than predicted. It was established that the method of tool construction, chosen because the tool was to be heated, had led to a lower friction coefficient than with standard cold tooling. Specifically, the P20 tool steel with full nitriding and high polish appeared to have a Coulomb friction coefficient up to 0.04 lower than standard. It was necessary to modify the tooling to increase severity by tightening radii, increasing draw depth and hence increasing the blank size in order to meet the initial conditions of a good panel in steel and a failed panel in 5754 aluminium at room temperature.

Once these changes were made, the tool was re-tested and it was confirmed that a good panel to full depth (140mm) could be produced in DX54 mild steel, but 5754-H111 aluminium at room temperature failed at least 50mm from full depth (Figure 5).

Having confirmed that the tool was performing within the defined bounds, a full suite of test cases were run. The initial tests were nominally isothermal – in other words the three elements of the tool (upper die, lower ring and lower punch) were all heated to the same temperature using the inbuilt cartridge heaters, and the blank was heated to the same temperature in a box oven before manually positioned and the press turned over. The objective of these manual trials was to establish the safe process window before moving to a run-at-rate test using a conveyor oven and robot loading cell.

Figure 5: Press Trial of Demonstrator Tool run with 5754 Aluminium at Room Temperature

The parameters studied in the manual trials included:

- Temperature, isothermal from room temperature up to 350°C and then introducing differential temperatures between either the blank and tools or different temperatures in different tools
- Blank size and shape
- Blank location
- Blankholder cushion pressure
- Lubricant

These parameters all interact to make the achievement of a safe working process window challenging. In particular, a change of lubricant to a graphite-based system was required in part due to the need to run the tooling at a higher than expected temperature combined with the time required to heat the blank to the required temperature. These circumstances were in part driven by the lack of ability to alter the press speed; the press available for the trials was a mechanical press with minimal ability to change the slide velocity (as would be the case with a hydraulic press, for example). A greater increase in formability would be expected with a lower rate of forming, based on the material test data and the findings from previous work – but this option was not available for these trials.

During the trials, in which several hundred panels were pressed, it became clear that the warm forming process was successful in producing enhanced formability with 5754 aluminium, but the process was sensitive to variations in inputs such as blank location. The optimum conditions with the tooling and press available for the trials appeared to be with the punch temperature slightly lower than the other tools and blank, using the graphite-based lubricant applied to the blank prior to heating. With these settings it was possible to run the automated production cell with the blanks heated in a conveyor and transferred to the press using a robot to produce a series of good quality panels.

6 Correlation

Once the isothermal tests had been carried out and a reasonable process developed it was then possible to return to the simulation models and examine the degree of correlation that had been achieved, and refine the models as necessary. For the selected cases for correlation, the following data was collated:

- Visual inspection of the panels for splitting and wrinkling
- Ultrasonic thickness measurements at 21 points along two different sections
- Edge movement at 8 locations around the blank

An example of the results achieved with the *MAT_036 is shown in Figure 6. The measured data indicated a very encouraging degree of correlation between test and simulation. Similar results were obtained for several other isothermal cases.

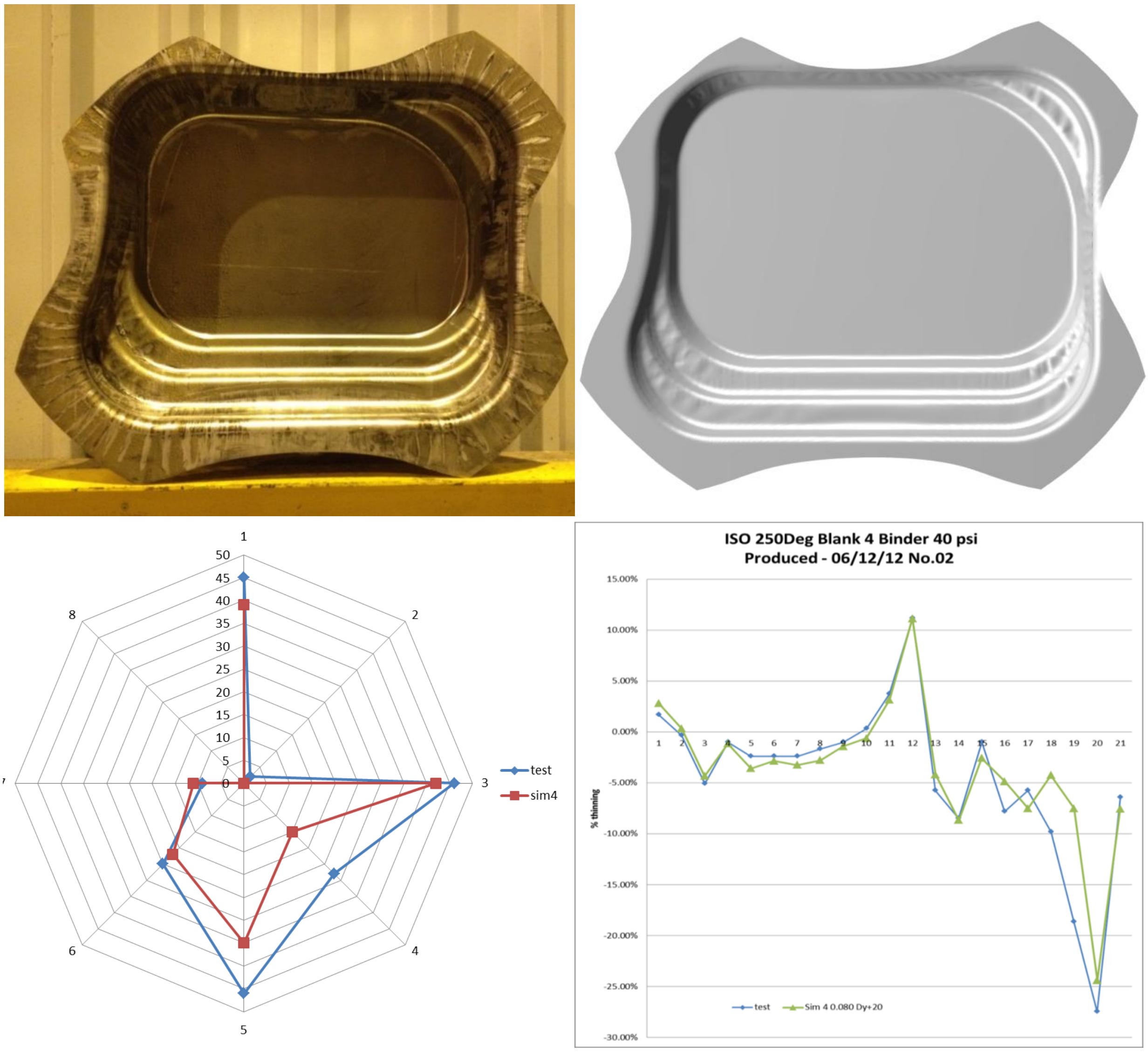

Figure 6: Correlation results for Isothermal Trial at 250°C showing (clockwise from top left) formed panel from the trial, image from simulation, thickness results and edge movement results

The simulation work can now be extended to consider non-isothermal cases by introducing heat transfer through a coupled thermal-mechanical calculation. LS-DYNA can be used for this as *MAT_036 can now accommodate stress-strain variation not only with strain rate but also temperature, using a 3D Table definition. The FE model will need to be developed to use of a solid (hex) mesh for the tooling and by adding thermal contact between tools and blank, with heat transfer coefficients dependent on pressure.

Given that the optimum process settings require a non-isothermal setup, the use of a FLD at a specific temperature to predict feasibility is not possible. Further work using the CDM model is required to predict damage to support the development of the warm forming process – but the work to date does show that the thinning predictions from the *MAT_036 model can already provide a good indication of whether the process will be acceptable in production.

7 Conclusions

LS-DYNA has been used to develop a stamping tool for testing the benefits of increased formability with warm forming of 5754 aluminium. Two simulation methods were applied in combination using material data from a range of material characterization tests.

A large number of panels have now been produced using the demonstrator tool cell and the correlation to simulation has been examined. Good correlation has been achieved for iso-thermal conditions using the latest version of the *MAT_036 material model with strain rate sensitivity.

The demonstrator cell has indicated that the warm forming process does achieve enhanced formability for 5754 aluminium compared with room temperature forming, and does allow a panel to be produced in aluminium that could only previously be formed in steel. The optimum conditions, based on the equipment available in the WAFT project, appear to be a non-isothermal tooling setup with the punch velocity slightly lower than the rest of the tools and blank. Successful formability prediction for this case requires both enhancing the work with the *MAT_036 model, to introduce coupled thermal-mechanical simulation, and also further testing of the CDM-based model.

8 Acknowledgments

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