Simulation of Warm Forming of Aluminium 5754 for Automotive Panels

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Abstract

The work described in this paper has been carried out as part of a project investigating implementation of an innovative metal forming process into the automotive industry to produce lightweight, high accuracy, complex-shaped automotive Aluminium panel components using one operation. The project, lasting three years, is a collaboration between industrial and academic partners lead by a Premium Automotive Manufacturer with funding from the UK Technology Strategy Board.

As part of the objective to not only investigate but also industrialize the technology, finite element simulation methods have been included in the scope of work. This paper will report on the extensive program of material characterization carried out by the academic partner Imperial College London in order to develop and correlate the simulation models. Focus is on the sensitivity of key material properties to both temperature and forming rate, as well as the variation of friction with temperature for various lubricants.

The Simulation method has been developed on two fronts. The initial approach takes an existing model and applies it to warm forming processes, chiefly under isothermal conditions; the required input parameters will be discussed. In parallel, a new and more comprehensive user-defined material model incorporating not only thermal and strain rate parameters but also a continuum damage mechanics (CDM) approach has been developed at Imperial College. The capability of the model to predict Forming Limit Curve measurements of 5754 aluminium sheet at various temperatures will be shown. The project is now in its final phase of forming trials using a prototype tool that has been manufactured based on the simulation work to date.

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, a collaboration of high profile manufacturing, consultant and academic partners, is known as WAFT – Warm Aluminium Forming Technology – and is part-funded by the UK Technology Strategy Board.

The opening premise for the work was that increased formability could be achieved with existing aluminium grades when heated to temperatures approximately in the range of 200°C to 350°C [1]. At these temperatures, the material does not undergo re-crystallization or achieve superplasticity, but it has been shown that increased formability (in terms of e.g., limiting dome height tests) can be achieved – but the exact combination of blank and tool temperatures, and also forming rate, were not yet known.

The project aim is to industrialise the innovative warm forming concept, in essence marrying the commercially existing worlds of superplastic forming for niche production with the conventional cold processing technique used in volume production today. The outcome is to provide a manufacturing process specifically optimised for premium vehicle production, the aim being to achieve steel formability with aluminium.

The grade of aluminium chosen for the study is 5754; this is already widely used for cold forming of aluminium panels for automotive body-in-white structures and issues regarding assembly and structural behaviour in the vehicle are already well understood. However, the reduced formability of 5754 compared with steel drives body-in-white design to adopt simpler forms and more numerous parts, with more sub-assembly 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.

This paper presents key aspects of the material characterisation and finite element simulation tasks required to support the final outcome of the project – i.e., an industrial cell running a demonstrator tool at automotive production rates. This cell is currently being commissioned and the final results will be disseminated after the project is completed in November 2012.

Simulation Objectives

In order to apply the WAFT process on an industrial scale, the automotive OEM involved in this project (like virtually all OEMs worldwide today) will require a simulation tool to be used during the product development stage for any new vehicle. Hence simulation is seen as a key part of this project. Not only that, but simulation was also required to evaluate the panel (and hence stamping tool) design to be utilized in the industrial demonstrator cell.

However, successful implementation of simulation methods for warm forming will require consideration of parameters normally not considered for cold stamping processes – in particular temperature dependent material properties and heat transfer between tool and blank, but also strain rate sensitivity which was known to be a factor in the formability of warm aluminium.

Forming feasibility has for many years relied upon the concept of a forming limit diagram (FLD) to determine if a part can be safely formed. This empirical method, based on tests of strips of material of varying width formed using a dome or cylindrical punch, has proved extremely useful – though it does have some limitation, notably the assumption that all regions of the blank have similar characteristics even when they have been formed under different conditions. This is already a difficulty in cold stamped parts with non-linear strain paths.

The limitation of the FLD is exacerbated in warm forming. When the blank material is heated its formability changes and the amount of change depends on the exact temperature distribution over the blank. Moreover, it has been observed that warmed material shows an increasing sensitivity to strain rate. Hence, the stress-strain relationship and other material characteristics can no longer be assumed to be constant over the blank; and the Forming Limit Diagram (based on tests conducted at a specific temperature and strain rate) can no longer be relied on to determine if a panel will split or not.

In order to deal with the increased complexity for WAFT a two stage strategy was adopted. The first approach was to use an existing material model already available in LS-DYNA ®, making any simplifying assumptions as necessary – initially this meant assuming isothermal conditions and a fixed strain rate; the three parameter Barlat model (*MAT_036) was selected. 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 material formability under all possible process conditions; this is referred to in the following paper as the continuum damage mechanics (CDM) model.

Material Characterization

Test-pieces were produced from commercial alloy AA5754; AA5754 offers good corrosion resistance, weldability and excellent formability. The material was supplied by Novelis UK Ltd in the form of 400 x 400 x 1.5mm sheet, in H111 condition (coil/batch number 7506180/982270). The chemical composition of the alloy is shown in Table 1. It has a 0.2% proof stress of 121MPa, a tensile strength of 234MPa and an elongation (A80) of 25% [2].

Table 1. The Chemical composition of AA5754 [2].

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt%	0.08	0.16	0.004	0.45	3.2	0.001	0.01	0.02	Bal.

Experimental method

Two sets of experimental data were used both to populate the Barlat 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 system).

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 grids (pattern), and for determining limit strains according to the ISO 12004-2:2008 standard.

The results of the stress-strain and FLD tests are shown and compared with the values predicted by the CDM model in the figures below.

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 and characteristics noted in current automotive body-in-white parts. The panel includes a number of steps and corners of different plan radii, as well as an optional embossment on the punch face. Forming simulation using DYNAFORM (with the LS-DYNA solver) was employed to evaluate the details of the design; this had to be completed early on in the material characterization phase of the project so a number of assumptions had to be made. The objective was to design a panel that was (a) formable in cold mild steel in terms of splitting, thinning and wrinkling (but approaching the failure limits), (b) not formable in aluminium at room temperature and yet (c) potentially formable in aluminium using a warm forming process.

The material model typically used for simulating the forming of aluminium sheet is *MAT_036, based on the yield surface developed by Barlat & Lian [3]. This model accounts for the anisotropy in the plane of the sheet due to rolling using the three 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 at Imperial. For the warm cases, a constant strain rate was assumed and a stress-strain curve from test at that rate and temperature was applied. There was no consideration of heat transfer or varying strain rate in the analysis. Friction conditions were also considered; the intent is to use a lubricant for the warm forming process which is expected to provide a very low coefficient of friction; values were determined in tests of different lubricants at a range of temperatures.

Figure 1 shows a typical result of thinning for a warm aluminium blank in the tool design during the development phase, analyzed as described above.

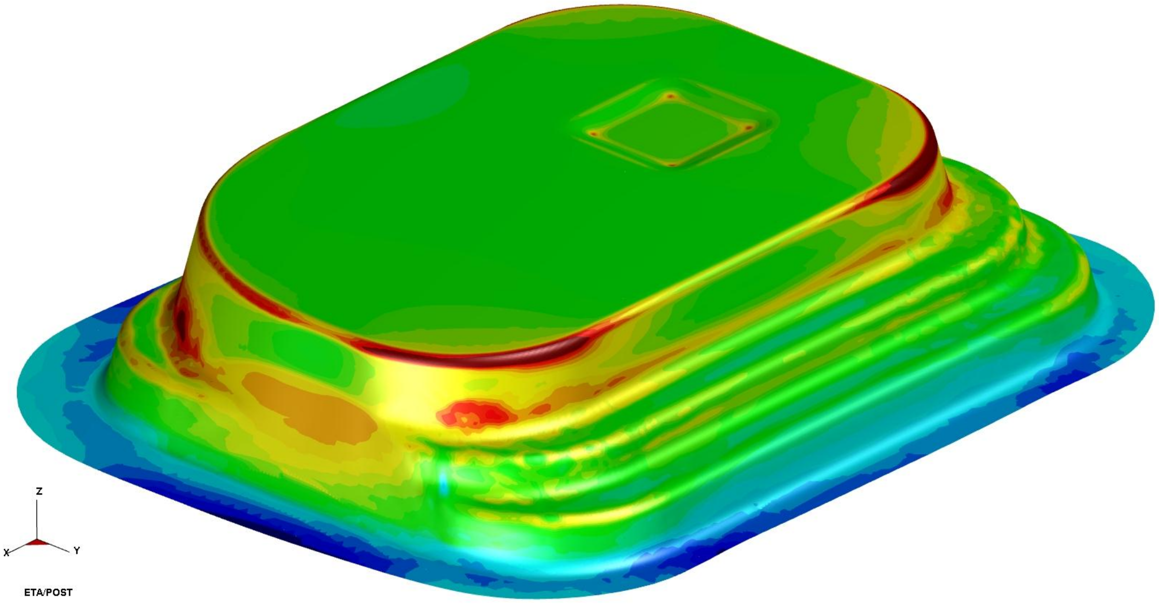

Figure 1 Example of a thinning result for the WAFT prototype tool, using *MAT_036 model

The latest release of LS-DYNA (R6) now offers an option for *MAT_036 to define stress vs strain as a tabulated input with both temperature and strain rate dependency. The R values can also be defined as a function of temperature. These options are now being investigated as part of the correlation to the tool trials. However, the problem of predicting the failure when temperature and strain rate are affecting formability still remains.

Development of a New Material Model

A new material model has been developed and calibrated from experimental data for AA5754 for isothermal uniaxial tensile and FLD tests over a temperature range of 20 to 300°C, and at strain rates ranging from 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 the consideration of a dissipation potential function [4-7]. With consideration of initial yield stress, k , a set of multi-axial viscoplastic constitutive equations, incorporating multiaxial damage evolution, may be written as:

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

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

$$\dot{R} = 0.5 B \bar{\rho}^{-0.5} \dot{\bar{\rho}} \qquad (3)$$

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

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

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

where $\dot{\varepsilon}_e^p$ in Equation (1) is the plastic strain rate which is formulated using the traditional power law. The evolution of material hardening, R , is given by Equation (3), which is a function of the normalised dislocation density, defined as $\bar{\rho} = (\rho - \rho_i) / \rho_m$, where ρ_i is the dislocation density for the virgin material (the initial state), and ρ_m the maximum (saturated) dislocation density that the material could have. Thus ρ varies from ρ_i to ρ_m , and normalized dislocation density, $\bar{\rho}$, varies from 0 (the initial state) to 1 (the saturated state) on the condition that $\rho_i \ll \rho_m$. Further details of the dislocation hardening formulation are given in [7]. The quantity D_{ijkl} in Equation (5) is the fourth order tensor of elastic constants. The multi-axial damage, Equation (6), comes from the uniaxial form by extension to a multiaxial stress state.

The viscoplastic damage constitutive equations are a set of non-linear ordinary differential equations. They cannot be solved analytically. Here, a numerical integration method is used to solve the equations [8]. The determination of material constants in unified constitutive equations is not an easy task and significant efforts have been made over the years [9-11]. In this research, an evolutionary algorithm (EA-based) optimization method detailed by Li et al. [10] and Cao and Lin [11], are used for the determination of the constants arising in the equations from experimental data.

In this application, calibration of the CDM model is achieved by fitting both the experimental uniaxial tensile and FLD data for AA5754 for different temperature and strain rates. Figure 2 shows the fitting results for the computed uniaxial viscoplastic damage part. Good agreement between the computed and experimental data exists. Calibration of the multi-axial part of the CDM model is carried out using the experimental FLD. The fitting result for the computed (solid curve) and the experimental FLDs (symbols) for AA5754 are shown in Figure 3. It is generally accepted that this difference is due to different strain measurement methods.

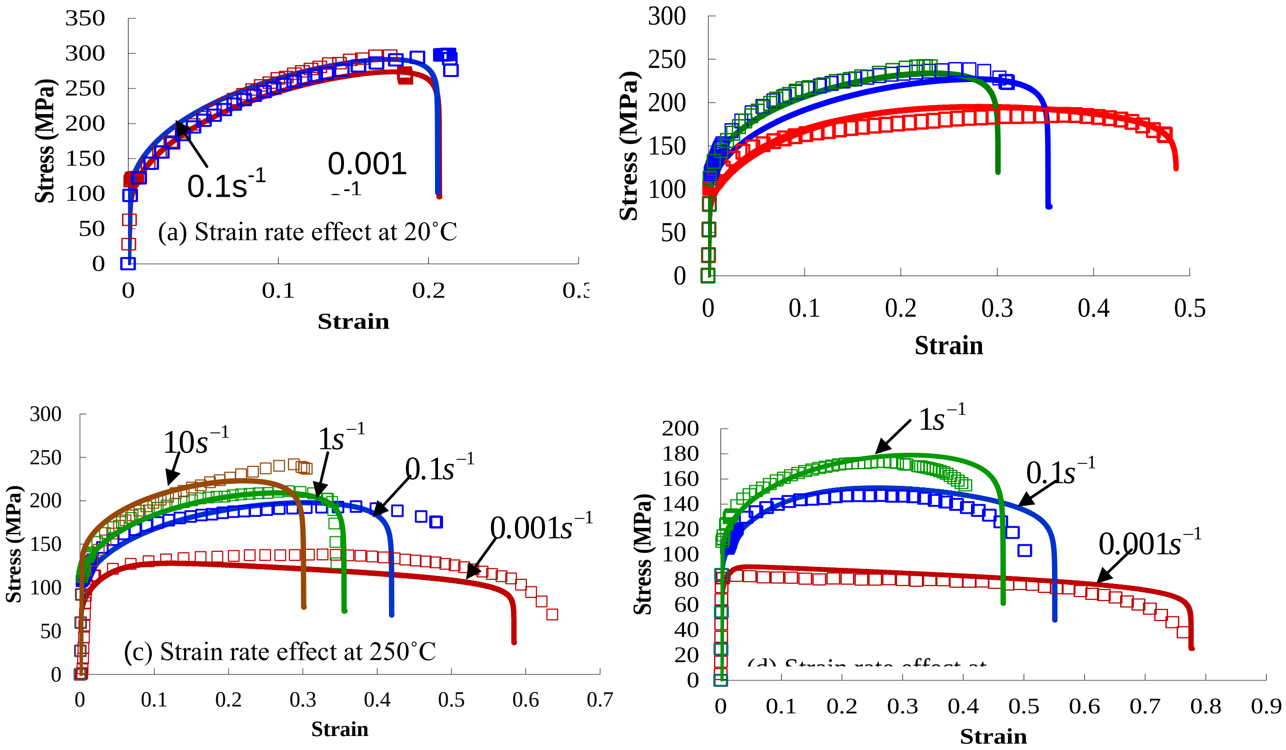

Figure 2 Comparison of experimental (symbols) and computed (solid curves) stress-strain relationships for different temperatures and strain rates.

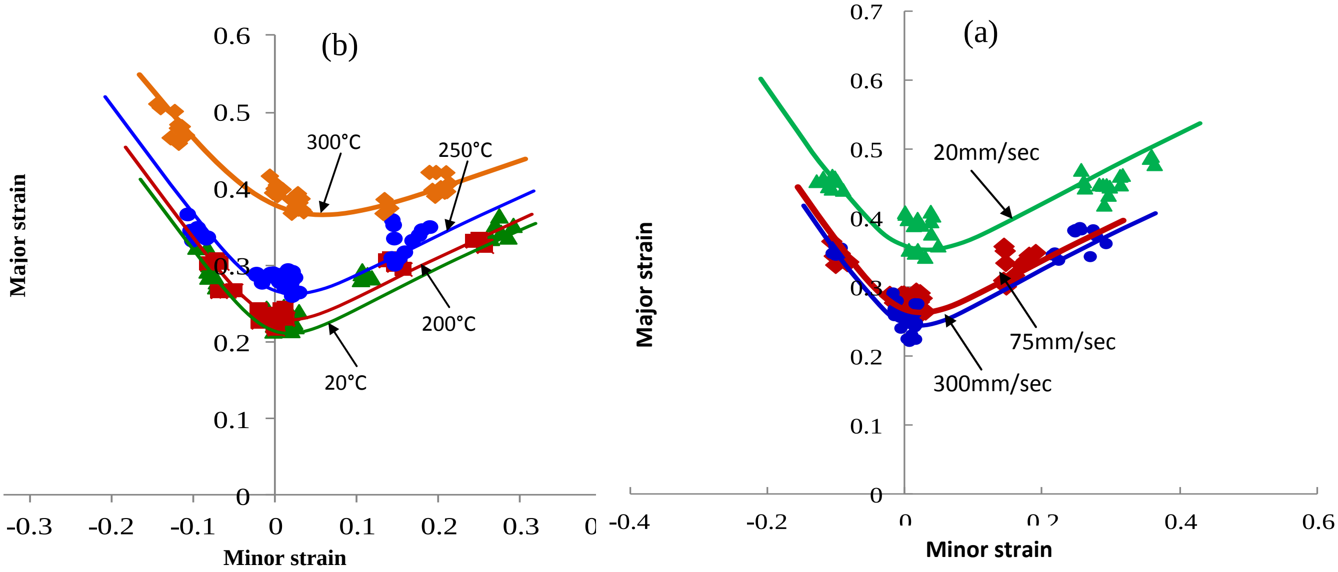

Figure 3 Comparison of experimental (symbols) and computed (solid curves) FLDs for (a) different forming rates at a temperature of 250°C and (b) different temperatures at a forming rate of 75mms^{-1}.

Simulation Using the CDM Model

A quarter symmetry finite element model for simulating the warm forming cup draw process is shown in Figure 4. The blank is modelled using a 4-noded thin shell element. The blank, diameter 160mm and thickness of 2mm, is deformed by a semi-spherical punch with diameter of 80mm, with a fixed top die and lower blankholder (binder) with varying spring force applied. The FE process modeling starts with applying the boundary and loading conditions on the model as shown. Once the punch moves toward the sheet, the first contact occurs between the sheet and blank holder. The blank holder force (BHF), with values in the range 0, 10, 20, 50, 100 and 1000kN, is applied to investigate the effect of the BHF on formability (splits) and wrinkling during the deformation process. The stroke applied is 50mm in 0.5s (100 ± 0.01mms^{-1}).

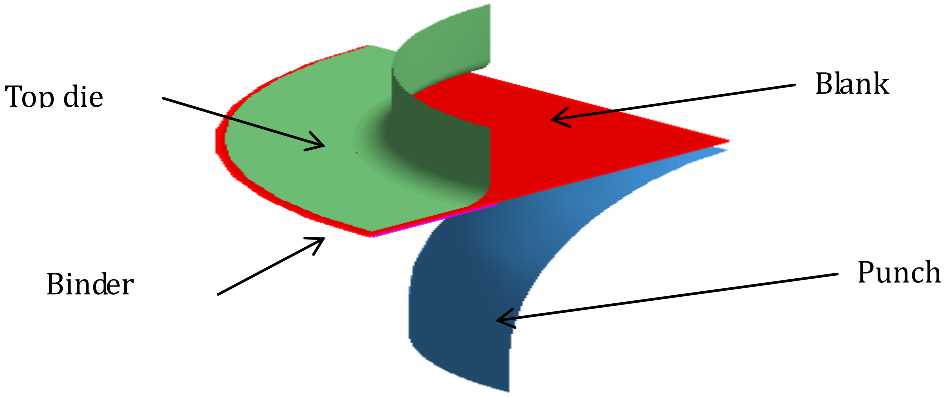

Figure 4 FE model for forming a spherical cup part.

Figure 5 shows the dependency of formability on the combined effects of BHF and temperature. The BHF controls the sheet metal forming. The formability of the cup part in this study comes from two crucial sources: drawability and stretchability. The stretchability generally increases with increasing forming temperature; however, the drawability increases dramatically with decreasing BHF but is degraded by wrinkling, which diminishes as temperature and/or BHF increase.

In this study fracture and wrinkling are taken as the process limits. Failure by fracture is checked using the relevant damage parameter. According to the viscoplastic damage model developed above, the damage parameter is zero (undamaged) at the beginning of the deformation, and remains zero until damage initiates, at which point the damage parameter begins to rapidly increase as the failure of the material is approached. In this way, the fracture of the material (hence the fracture strain and/or depth to fracture) can be identified by the damage parameter attaining a critical value, taken to be 0.7 for AA5754 in this study. However, failure by winkling along the flange circumference must also be monitored.

For successful manufacture of a component using warm forming, correctly choosing the process parameters is essential. The BHF and temperature are the most important factors, which are studied in depth to define the process window for the forming process. To determine the process window numerically, a series of FE forming process simulations with different BHFs and drawing depths were carried out. To define a boundary point of the process window for a given BHF, a simple bisection method was used. Figure 5 represents the process window for isothermal warm forming process for AA5754 deformed at temperature of 250°C and forming rate of 75mm/sec. The upper bound of the formability limit is the failure region due to wrinkling and/or tearing. The lower bound is the quality part region in which the part is deformed successfully without failure or wrinkling. The failure region is again divided into two regions, the left region representing the failure due to wrinkling and the right region representing failure due to tearing. As mentioned previously, failure due to tearing is checked by using the relative damage parameter in which the material failed as the damage reaches 0.7. However, wrinkling is checked based on the relative movement of the blank holder due to the formation of wrinkling at a given BHF. As the blank holder displacement reaches 100% of t, wrinkling is monitored, where t is the blank thickness.

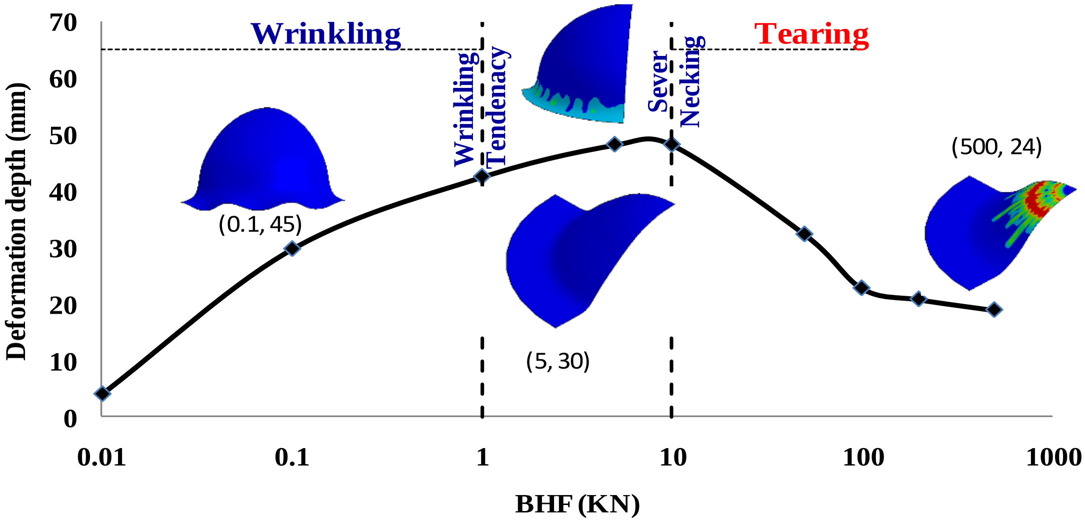

Figure 5 Effect of BHF on formability in terms of part depth to failure of AA5754 tested at temperature of 250°C and forming rate of 75mm/s.

Further Work

At the time of writing, the industrial demonstrator production cell is being commissioned in order to carry out a full set of experiments. A number or parameters will be studied; blank temperature (heated in a conveyor oven), individual tool temperatures (die, punch and blankholder can all be heated independently using cartridge heaters), blankholder force (cushion pressure), friction (by varying the type and amount of lubrication) and other process details including blank size and removable tool elements (punch inserts, plates). The tests will allow us to determine the best combination of blank and tool temperatures to give the greatest enhancement in formability within the acceptable bounds of splitting, thinning and wrinkling as described above.

With this data we will be able to correlate the two simulation methods (both *MAT_036 with the latest available features and also the new CDM-based material model, refined against the most up to date material data). Hence we expect to be able to determine the production simulation process to be applied by the automotive manufacturer in order to implement warm forming technology in the design of forthcoming automotive body-in-white structures.

Conclusions

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

The second method presented here uses novel plane-stress CDM-based viscoplastic constitutive equations, which have sufficient flexibility for the prediction of the FLD curves for sheet metals under various hot stamping conditions. The model is calibrated using data from isothermal warm tensile tests for different temperatures and strain rates. This model provides a good fit to the experimental flow stress strain relations, including the strain softening region. The determined CDM equations can predict the experimental FLD data over a temperature range of 20 to 300°C and forming rates of 20 to 300mm/s for AA5754.

The simulation methods will now be evaluated against the results from the upcoming industrial demonstrator trials.

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