Advances in FEM Simulation of HFQ® AA6082 tailor welded blanks for automotive applications

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Abstract. Vehicle weight reduction has been identified as one of the most effective ways of achieving reduced energy consumption and CO2 emissions in the automotive industry. Aluminium has been used as a lightweight replacement to steel in the automotive industries for many years. In addition to the high specific strength, the formability of high-strength sheet aluminium is increased significantly at elevated temperatures. New manufacturing technologies that allow forming of high and ultra-high strength aluminium alloys have emerged recently. One such technology is HFQ® - solution heat treatment, forming and in-die quenching which combines material tempering with mechanical deformation. In this article, firstly, HFQ® Technology is used when forming a uniform thickness blank and, secondly, further benefits are shown when combining the HFQ® technology with friction stir welding. The friction stir welded AA6082 tailor welded blanks (TWBs), with gauge of 2.0-3.0 mm have been prepared and successfully formed into automotive components using the HFQ® process. The recent advances in the FE analysis and the implementation of a novel CDM model in industrial applications of the HFQ® process has been described. This paper presents the use of CDM, integrated into FEA package Pam-Stamp, to accurately predict the forming of an automotive tailor welded cross member panel.

1. Introduction
A process which combines high formability with virtually no springback for (ultra) high strength aluminum alloys was developed and patented by a team of researchers based at Imperial College London [1] and commercialized by a spin-off company - Impression Technologies Ltd (ITL) [2]. The process is called Solution Heat Treatment, Forming and in-Die Quenching, shortened to Hot Form Quench or HFQ. It consists of heating an Al-alloy sheet to its Solution Heat Treatment (SHT) temperature to produce a homogeneous solid solution with high ductility and hence good formability. The blank is then transferred to the press where high forming speed is used to take advantage of strain rate hardening of the material [2]. The formed part is held in the tool for a few seconds to quench the alloy to avoid the formation of precipitates in the microstructure (see Figure 1) [3,4]. In order to identify the proper forming conditions for different aluminum alloys, the formability limit and the ductile fracture initiation characteristics must be correctly predicted for the relevant sheet forming process; knowledge of the failure features is essential. The classical FLDS show the critical combination of major and minor surface strains in a metal sheet at the onset of necking failure. These have been established for fixed values of
temperature and strain rate but cannot be used directly to predict the forming limit of sheet metal in hot stamping, due to the dynamic changes in temperatures and strain rates. Continuum Damage Mechanics (CDM)-based theories have been developed to predict the damage process and accurate failure prediction of forming the complex-shaped automotive panel component (cross member part) [4].

Figure 1. The HFQ® technology process steps. The blank is heated up to the solution heat treatment temperature (alloy dependent) until it is completely solutionised. The blank is formed and quenched into the cold dies.

2. Experimental program

The forming trials of an automotive cross member panel have been carried out at ITL. Three different blank types are used. Type A: blank with uniform thickness of 2mm; Type B: blank with uniform thickness of 2mm but different geometry; Type C: TWB with thicknesses of 3.0:2.0:3.0 mm. Two different forming conditions were carried out; slow HFQ® process (forming speed below 50 mm/s) for blank A and fast HFQ® process (forming speed above 100 mm/s) for blank B and C. Figures 2, 3 and 4 show the formed panel of slow and fast forming rates for blank A, B and C. As shown in Figure 2, there is a crack on the emboss highlighted in Figure 2, however all the features of the part are successfully formed. A slow forming rate gives a lower forming temperature and lower strain rates, which results in significantly reduced ductility and flow. On the other hand, a fast forming speed maintains a higher temperature and higher strain rates during forming and enhances the high ductility of the material [7]. This higher ductility and flow is shown in Figure 3 (blank type B) in which the part is successfully formed. The emboss feature which is split in the slow forming rate is formed without defects at high forming rate. The successful formed blank type B comprises of a TWB with thickness combination of 2:3 (mm:mm) (Blank type C) as shown in Figure 4.

Figure 2. Failure regions from the low speed forming (below 50 mm/s) of the blank Type A cross-member panel part of 2 mm thickness.
3. Description of the analytical CDM model for aluminum alloys

A viscoplastic-damage constitutive model that takes the mechanisms of dislocation-driven evolution processes such as hardening, dynamic and static recovery and damage into account is presented below. A stress – elastic strain relation is given by [3, 4]:

\[ \sigma_{ij} = \frac{\sigma_{ij}}{1-\omega} = D_{ijkl} \varepsilon_{kl} \]  

(1)

where \( \omega \) is damage variable, \( D \) is elasticity tensor in which the Young modulus is assumed to depend on temperature.

The total strain can be written as a sum of elastic, viscoplastic and thermal strains:

\[ \varepsilon_{ij} = \varepsilon^{el}_{ij} + \varepsilon^{vp}_{ij} + \varepsilon^{th}_{ij} \]  

(2)

where the viscoplastic strain can be obtained from integration of the viscoplastic strain rate given by the following:

\[ \dot{\varepsilon}_{ij}^{vp} = \hat{p} \frac{3}{2f} s_{ij} \]  

(3)

\[ \hat{p} = \left( \frac{2}{3} \varepsilon_{ij}^{vp} \varepsilon_{ij}^{vp} \right)^{1/2} \]  

(4)

where \( \rho \) is the equivalent viscoplastic strain, which could be also written \( \varepsilon_{eq}^{vp} \), \( f \) is the equivalent Von Mises stress, (also written as \( \sigma_{eq} \)), \( s_{ij} \) is the deviatoric stress tensor.
Taking the isotropic hardening as a function of dislocation density, \( \rho \), we write:

\[
R = B \rho^{n_1}
\]

where dislocation density is integrated from:

\[
\dot{\rho} = A(1 - \rho)\dot{\rho} - C \rho^{n_2}
\]

Evolution of dislocation density \( \rho \) is related to the equivalent viscoplastic strain rate, it includes the dynamic recovery and the static recovery which appear at high temperature. Parameters \( A, B, C \) are function of temperature.

The Viscous stress:

\[
F = \tilde{f} - R - k
\]

where \( \tilde{f} = f(\tilde{\sigma}) \), \( k \) is the initial yield stress which is a function of temperature in our case, if \( F > 0 \) irreversible viscoplastic strain occurs.

Assuming a power law function for the equivalent viscoplastic strain rate we write:

\[
\dot{\rho} = \left( \frac{f}{K} \right)^n
\]

or

\[
F = k\dot{\rho}^\frac{1}{n}
\]

where parameters \( K \) and \( n \) are functions of temperature. The damage criterion is a combination of the three invariants of stress tensor \( J_0(\sigma), J_1(\sigma), J_2(\sigma) \), which are respectively the maximum principle stress: \( J_0(\sigma) = \sigma \), the first invariant: \( J_1(\sigma) = tr(\sigma) = 3\sigma_H \), the second invariant: equivalent stress \( J_2(\sigma) = f = \sigma_e \).

\[
X(\sigma) = \frac{\alpha_1 J_0(\sigma) + \alpha_2 J_1(\sigma) + \alpha_3 J_2(\sigma)}{(\alpha_1 + \alpha_2 + \alpha_3) J_2(\sigma)}
\]

or

\[
X(\tilde{\sigma}) = \frac{\alpha_1 J_0(\tilde{\sigma}) + \alpha_2 J_1(\tilde{\sigma}) + \alpha_3 J_2(\tilde{\sigma})}{(\alpha_1 + \alpha_2 + \alpha_3) J_2(\tilde{\sigma})}
\]

Where the parameters \( \alpha_1 \) is temperature dependent \( \alpha_2 \) is strain rate dependent and \( \alpha_3 \) is constant [4]. The three invariants allow representing two different damage mechanisms, namely the grain boundary damage and the ductile damage. Irreversible damage occurs if \( X > 0 \). Finally, the rate of damage accumulation is given by:

\[
\dot{\omega} = \Delta X^\phi \eta_1 \dot{\rho}^{\eta_2} \frac{1}{(1-\omega)^\eta_3}
\]

where parameters \( \eta_1, \eta_2 \) are assumed to be functions of temperature and parameters \( \eta_1, \phi, \Delta \) are assumed to be temperature independent. Damage parameter defined in Equation (12) is assumed to be 0 at the initial state of the deformation. When the damage level reaches 0.7, it is assumed that failure takes place in the material. According to the feature of the damage model, as the damage increases from 0.7 to 1.0, the strain increment is very small and can be omitted.

4. CDM model implementation testing
The details of the CDM model, including description and calibration, are explained deeply in previous author’s publications [4]. The calibration of the CDM model is achieved by fitting both the experimental
uniaxial tensile and FLD data for aluminum alloys at different temperatures and strain rates [5]. In this study, the CDM model is applied in industrial applications. In order to test the correct implementation of the CDM model into PAM-STAMP via UDM, a single element was tested under unidirectional tension at 500°C and at two different strain rates of 1s⁻¹ and 4s⁻¹ [6]. Figure 5 shows the comparison between the flow curves derived from the simulation and from the CDM model calibration data. These two curves, dashed line from PAM-STAMP and solid line from numerical, show good agreement. This indicates a correct implementation of CDM model into the FE software via external subroutine.

Figure 5. One element tensile model results at 500 °C at two strain rates (1s⁻¹ and 4s⁻¹). The dashed line is for the simulation while the solid line is from CDM model FE model and experimental validation [6].

A FE model has been created and validated using experimental results. Studies have been carried out to validate the novel CDM model [4, 5]. FE forming simulation of the front cross member part at elevated temperatures was conducted for AA6082 aluminum alloy using the fully coupled thermo-mechanical solver in PAM-STAMP. The CDM constitutive equations for AA6082 was implemented and tested via the user defined subroutine. The cross-member 3D FE model with boundary conditions is shown in Figure 6. The effect of heat transfer coefficient, HTC, was investigated by Foster, et al. 2008 [7]. The forming simulation was used to verify the ability to predict failure using the CDM model implemented into PAM-STAMP, compared against experimental results. The CDM model was also used to predict formability and thinning at elevated temperature.

Figure 6. 3D FE model of the cross-member panel part.

Figure 7 shows that the maximum thinning occurred for the cross-member panel at slow forming. The maximum thinning is predicted in the region where splitting occurs in the experimental trial (see Figure...
The CDM model was used to evaluate the maximum thinning relative to the failure limit. In this study, two different techniques have been used to apply the CDM model. The first one involves the study of selected critical elements which are showing maximum thinning, while the second is a fully integrated method which evaluates the whole part. The first method is useful for very low forming speed simulation due to the long computational time. This method involves the analysis of the history of element state variables (in example temperature and strain rate, maximum and minimum strains) where the maximum thinning occurred. Then, the strain path and calculated strain ratio are obtained. The limit of the damage value was calculated from the late stage of the deformation, where the stain is not changing with the reduction in stress (w =0.7). Using the CDM model, the forming limit for this element and its forming parameters was established as shown as red curve in Figure 7. The strain path of this element exceeded the forming limit which indicates a failure. This corresponds to the results in experimental trial (Figure 2).

![Figure 7. Thinning simulation results for blank Type A cross-member panel, b) predicted strain path of the selected element and its corresponding formability limit.](image)

By increasing the forming rate from below 50 mm/s to above 100 mm/s, the formability of the material during the HFQ® process is improved. High speed allows the material to preserve its high temperature during the forming process and enhances the high ductility of the material. In this case, the CDM model was fully integrated and applied to the whole part, as shown in Figure 8. From the simulation results, the maximum damage value is 0.086, which indicates no splitting in the part. Therefore, the part was formed successfully at this condition and this can be observed in Figure 3.

![Figure 8. a) Damage simulation results for blank Type B cross-member panel, b) predicted damage curve of the selected element.](image)

The third blank design is used to validate the CDM model for the TWB HFQ® part, with thicknesses of 3.0:2.0:3.0 mm. In this case, the fast HFQ® process (forming speed above 100 mm/s) is used. As shown in Figure 9, the maximum damage reach to 0.115 which indicates that the part is not splitting. To explore...
this further, Figure 10 shows 18 locations of the formed TWB panel for which the thickness was measured and compared with that obtained from the simulation.

Figure 9. Damage simulation distribution for blank Type C (TWB with thicknesses of 3.0:2.0: 3.0 mm) for the cross-member panel.

Figure 10. Successful forming of blank Type-C TWB cross-member panel at high speed forming.

Figure 11 shows the direct comparison of the experimental measurements (solid symbols) and computed measurements (solid line). A good agreement – less than 5% error- has been achieved for the TWB thickness combinations (2.0 - 3.0 mm) in terms of thickness distributions, suggesting that the FE simulation can accurately represent the forming of TWB with various thicknesses, except for point 5 which gave a maximum error of 11%, as shown in Figure 12.

Figure 11. Comparison of thickness distribution of the FE simulations (solid line) and experiments (solid symbols) blank Type-C TWB cross-member panel at high hot forming rate process.
5. Conclusions

This paper presents the effect of different process parameters on the formability of high strength Al alloy with the HFQ® technology. The forming rate significantly affects the formability of the material during HFQ® process by preserving its high temperature. In this work, two forming rates have been used in the HFQ® trials for a cross-member panel. The blank formed at slow speed splits on the top emboss. However, at high forming speed the part is successfully formed without splitting. A new CDM model was implemented and used to simulate the formability of a part. Experimental results are in agreement (below 5% error) with the simulation results. This suggests that the current simulation capabilities can accurately simulate the forming of TWB with various thicknesses.

6. References

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