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An Industrial application of the continuum damage mechanics (CDM) model for predicting failure of AA6082 under HFQ® process

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Abstract

The failure prediction for forming of high strength complex shaped panel made of AA6082 aluminium alloy during the solution heat treatment cold die forming and quenching process (HFQ®), is presented. Experimental trails have been carried out to optimise the blank shape on the success of forming the complex-shaped aerospace panel component (wing stiffener part). Using the traditional set of uniaxial constitutive equations is difficult to predict the forming features in real hot stamping, especially taken the varied stress states during the forming process. A multi-axial viscoplastic constitutive model based on continuum damage mechanics (CDM) has been developed to describe the deformation behaviour of aluminium alloys under hot/warm stamping conditions. By linking such CDM-based constitutive equations into complete finite element solver, PAM-STAMP in this case, via external Subroutine, as a User Defined Material (UDM), the formability for any process conditions, cold or hot and low or high speed, could be predicted. In this paper the CDM model is verified using an experimental forming trail of complex aluminium component. The results show that the CDM model can be used to provide accurate formability and failure predictions.

Keywords: HFQ, Aluminium alloy, CDM model, FE simulation.

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1. Introduction

A process which combines high formability with virtually no springback for (ultra) high strength aluminium alloys was developed and patented by a team of researchers based at Imperial College London [1] and commercialised by a spin-off company - Impression Technologies Ltd (ITL) [2]. The process is called Solution Heat Treatment, Forming and in-Die Quenching, or HFQ® † for short. 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 tool speed is used to take advantage of strain rate hardening of the material. The formed part is held in the tool for a few seconds to quench it in order to avoid the formation of precipitates in the microstructure (see Fig.1) [3,4]. In order to identify proper forming conditions for sheet of a given aluminium alloy, 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, which show the critical combination of major and minor surface strains in a metal sheet at the onset of necking failure have been established for fixed values of temperature and strain rate, cannot be used directly to predict the forming limit of sheet metal in hot stamping in which the temperature and strain rate vary dynamically. Continuum Damage Mechanics (CDM)-based theories have been developed to predict the damage process and accurate failure prediction of forming the complex-shaped aerospace panel component (wing stiffener part).

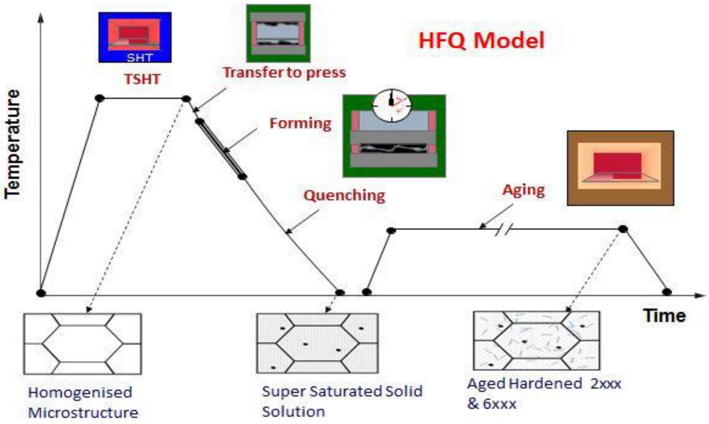


Fig.1. The HFQ process in a nutshell

Nomenclature

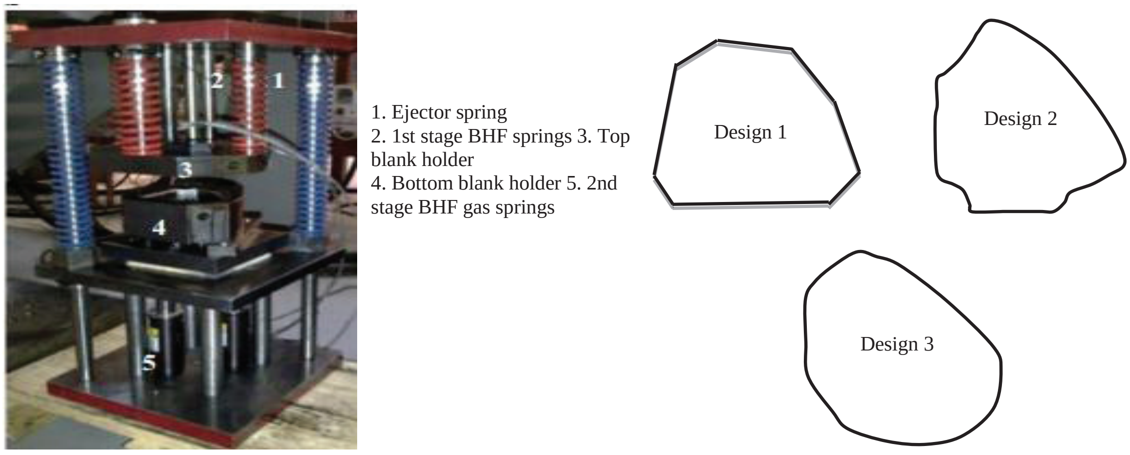
D_{ijkl}	Elastic matrix of the material
E	Young's modulus
R	Isotropic hardening
S_{ij}	Deviatoric stresses
T	Temperature
$\dot{\varepsilon}_e^P$	Plastic strain rate
ε_{ij}^P	Plastic strains
ε_e^P	Effective plastic strain
σ	Stress
σ_e	Effective stress

HFQ® is a registered trademark owned by Impression Technologies Ltd.

ω	Damage state variable
$\rho, \bar{\rho}$	Dislocation density, and normalised dislocation density

2. Experimental Programme

Forming trials of the stiffener part were carried out on a 25-ton high speed hydraulic press with a custom tool and die set as shown in Fig. 2a. These trials were carried out based on the optimization of process parameters (temperature, time, friction (lubricant) and blank holding force) to achieve successful formed parts. The deformation trials were conducted using the HFQ® process. The results of the tests were used to verify the simulation set-up for the HFQ® process using CDM model. The test specimen was first heated in a furnace to the target temperature, monitored using a thermocouple wire attached to it, and then quickly and carefully placed in the tool in under 10 s transfer time. The press was then activated stamping the specimen. Due to the complexity of the part, the formability and failure prediction were carefully considered. Blank shape also plays a crucial rule in successful forming of the part. Three iterations for the blank shape were performed for this part as is shown in Fig.2b.



1. Ejector spring
2. 1st stage BHF springs 3. Top blank holder
4. Bottom blank holder 5. 2nd stage BHF gas springs

(a) (b)

Fig.2. Stiffener tool set.

3. Computational Work.

3.1. The CMD model in a nutshell

Over the last couple of years, the CDM model has been extended to account for the effect of stress state on damage accumulation and failure. Different shapes of forming limit curves (FLCs) under hot stamping conditions could be predicted with different temperatures and strain rates. Implementing this CDM-based constitutive equations into the FE code (PAM-STAMP) with a user-defined subroutine, allows the formability for any process conditions, cold or hot and low or high forming speeds, to be predicted by the FE simulations. A viscoplastic-damage constitutive model has been developed that takes the mechanisms of dislocation-driven evolution processes such as hardening, dynamic and static recovery and damage into account [4, 5].

$$\dot{\varepsilon}_P = \langle \frac{\sigma/(1-\omega)-R-k}{K} \rangle^n \tag{1}$$

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

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

$$\dot{\bar{\rho}} = A\left(1-\bar{\rho}\right)\left|\dot{\varepsilon}_p\right| - C\bar{\rho}^{n_2} \tag{4}$$

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

$$\dot{\omega} = \frac{\Delta}{\left(\alpha_1+\alpha_2+\alpha_3\right)^{\varphi}}\left\langle\frac{\alpha_1\sigma_1+3\alpha_2\sigma_H+\alpha_3\sigma_e}{\sigma_e}\right\rangle^{\varphi} \cdot \frac{\eta_1\sigma_e}{\left(1-\omega\right)^{\eta_3}}\left(\dot{\varepsilon}_p\right)^{\eta_2} \tag{6}$$

Where $\dot{\varepsilon}^{p}_{e}$ 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 normalised dislocation density, defined as $\bar{\rho} = (\rho - \rho_0)/(\rho_m - \rho_0)$ [5]. The parameters $K, k, B, E, C, \eta_1, \eta_2, \eta_3, A, n, \varphi$ and Δ are temperature-dependent material constants. Equations in Table 2 represent the temperature-dependent parameters. D_{ijkl} is the plane stress elastic stiffness matrix of the material. The multiaxial damage Equation (6) comes from the uniaxial form with consideration of the multiaxial stress-state effect. α_1, α_2 and α_3 are used to calibrate the effect of maximum principal stress, hydrostatic stress and effective stress on damage evolution respectively. If α_1 or α_2 or α_3 is zero, the implication is that the particular stress has no contribution to the damage process. The symbol φ represents a parameter, which controls the effect of multi-axial stress values and their combination on damage evolution, thus determining formability. Symbol Δ is for a correction factor to unify for the different strain values measured by uniaxial tensile tests and formability tests [5].

3.2. CDM model implementation testing

In order to test the numerical stability and carry out some preliminary investigation of the CDM model above (as a UDM linked to PAM-STAMP via external subroutine), a single element case under unidirectional tension at 500°C and two different strain rates of $1s^{-1}$ and $4s^{-1}$. Fig.3 shows the one element tensile model and comparison between the numerical and simulated flow curves at 500°C and strain rate of $1s^{-1}$and $4s^{-1}$.

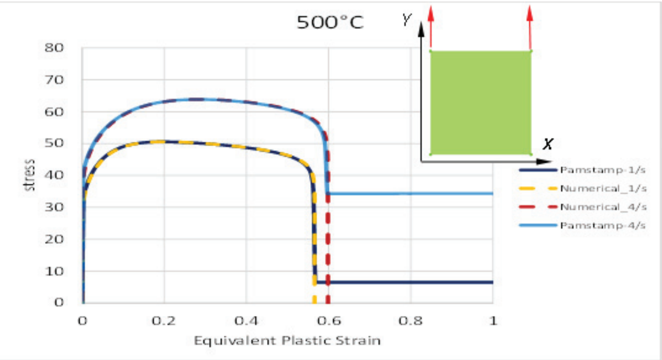


Fig.3. One element tensile model results from CDM model implemented into PAM-STAMP.

3.3. FE model and Experimental validation

An FE model has been created and validated using experimental results. Studies have been carried out to validate the novel CDM model. FE forming simulation of the wing stiffener part at elevated temperatures was conducted for AA6082 aluminum alloy using fully coupled thermos-mechanical solver in PAM-STAMP. The CDM constitutive equations for AA6082 was implemented and tested via the user defined subroutine, as explained above. The cross section 3D FE model with boundary conditions is shown in Fig. 4. The effect of heat transfer coefficient, HTC, was investigated by Foster, et al. 2008 [4], and the value of heat transfer coefficient was found to be, 1.4 (mW/mm^{2}C). The forming simulation was used to verify the ability to predict failure using the CDM model implemented into PAM-SATMP, in comparison against experimental results. The CDM model was also used to predict formability and thinning at elevated temperature.

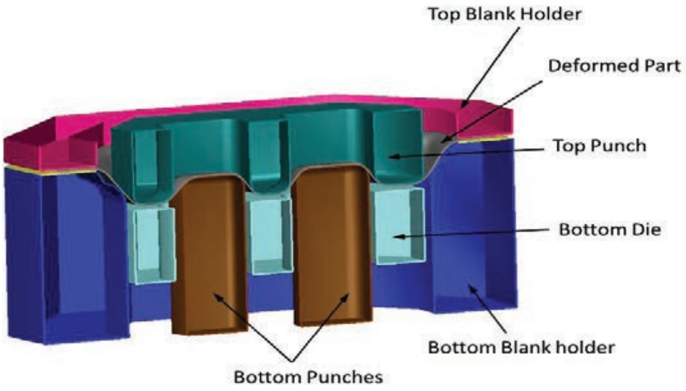


Fig.4. Cross section 3D FE model of the wing stiffener

The part is not successfully deformed using blank design 1. As shown in the experimental trail (Fig.5a), there is a crack on the corners of the inside triangle emboss. Fig.5b presents the simulation results showing the damage variable distribution. From the simulation results, the damage variable reached the critical threshold value of 0.7 which indicates the failure occurred. In addition to the damage variable the FE simulation allowed prediction of the thickness distribution for the part, as is shown in Fig.5c. From the results in the Fig. 5, it could be concluded that the CDM model allows accurate predictions of formability and failure.

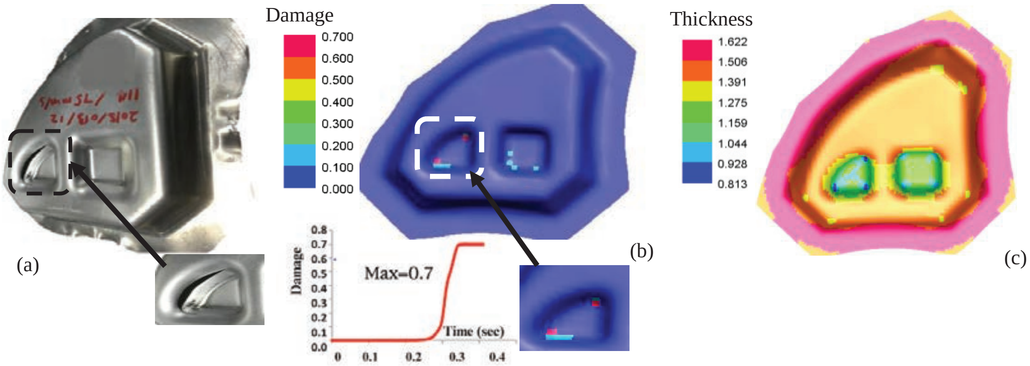


Fig. 5. Comparison of failure regions in HFQ® formed wing stiffener panel using blank design 1: a) experimental, b) FE simulation using CDM model showing damage distribution and c) FE simulation using CDM model showing thickness distribution.

By modification of the blank design 1 and eliminating the edge effects, blank design 2 was used in as the second iteration of the blank design process. In Fig.6a, the experimental result shows that there is no failure in the triangle emboss and the main feature of the part is formed successfully expect the two corners of the part. This is due to the less material in these areas causing more drawing of the material inside the die. Damage value was 0.115 as shown in the FE simulation results (Fig.6b) which indicates no failure occurrence, however, it is close to necking regions. The minimum thickness in Fig.6c occurred in the regions which are in a good agreement with damage value and also the experimental results.

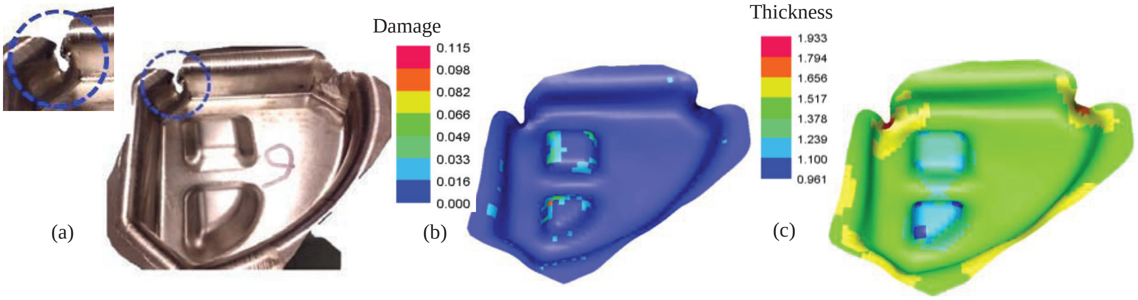


Fig. 6. Comparison of failure regions in HFQ® formed stiffener panel using blank design 2: a) experimental, b) FE simulation using CDM model showing damage distribution and c) FE simulation using CDM model showing thickness distribution.

Final iteration of the blank design was the blank design 3 which yielded successful part without any defects. This can be noticed from the experimental trails shown in Fig. 7a. The damage value of this case is 0.065 which indicates that the part is formed without risk of necking as shown in Fig.7b. Furthermore, the thickness distribution also indicates very good agreement between the CDM model and experimental trail.

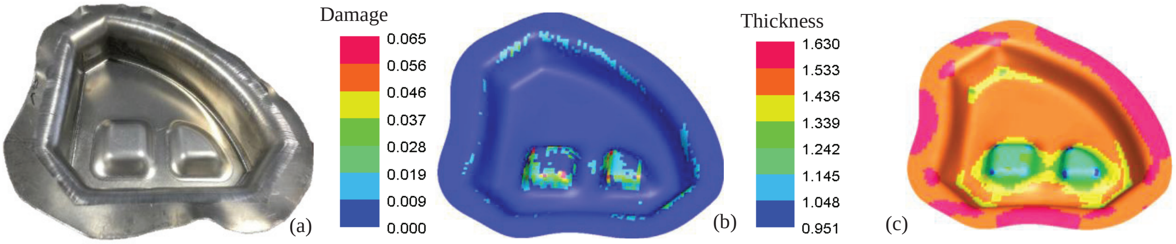


Fig. 7. Comparison of failure regions in HFQ® formed stiffener panel using blank design 3: a) experimental, b) FE simulation using CDM model showing damage distribution and c) FE simulation using CDM model showing thickness distribution.

Conclusions

This paper presents the application of the plane-stress continuum damage mechanics (CDM) model to achieve an accurate failure prediction of an aluminum alloy AA6082 wing stiffener part formed using HFQ® process. The model was calibrated using uniaxial tensile test and FLC experimental data for AA6082 at different temperatures and strain rates. The part was formed successfully following several iterations of the blank design and the formability prediction via CDM model helped in this process. The calibrated CDM model has been implemented into the commercial finite element code PAM-SATAMP via a user-defined material subroutine. A FE model has been created and validated from the experimental trails. From the experimental and simulation findings, it is concluded that the blank design 3 was the optimum design and the results indicate that the CDM model allows accurate predictions of formability and failure.

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