Stress-relaxation age forming of a component with complex and large curvatures: Simulation and Manufacturing

Qi Rong¹, Zhusheng Shi^{1,*}, Yong Li² and Jianguo Lin¹

¹ Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

² School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China

*Corresponding author. E-mail: zhusheng.shi@imperial.ac.uk (Z. Shi)

Abstract Stress-relaxation age forming (SRAF) of a component (820*300*3 mm³) with complex and large curvatures has been simulated and corresponding SRAF test of an Al-Mg-Si alloy, AA6082-T6, has been carried out in this study. An FE model is established to simulate the stress-relaxation ageing (SRA) behaviour of AA6082-T6 during SRAF at various stress levels, for the first time, ranging from elastic to plastic regions and a unified constitutive model for SRA of the material has been implemented into finite element (FE) software ABAQUS via the user-defined subroutine CREEP. An optimised tool surface was determined from FE simulation through springback predication and compensation and was used for manufacturing test. A good agreement of the formed shape has been achieved between the FE simulation and the SRAF test, with a maximum shape error below 4 mm, satisfying the industrial requirement. Hardness results from the formed plate show insignificant change of strength during SRAF, in good agreement with the simulation. The effects of the initial plastic strain and creep strain generated during loading and stress-relaxation stages on the formed shape have also been analysed.

Keywords Stress-relaxation age forming, Creep age forming, Large and complex curvature, FE simulation, Al-Mg-Si alloy.

1. Introduction

Stress-relaxation age forming (SRAF), which is also called creep age forming (CAF), is a sheet metal forming technology combining material deformation and age hardening in one process, and has been widely employed in the production of extra-large panels in the aeronautics industry [1, 2]. For example, SRAF method has been used for the production of upper wing skins of Airbus A380 superjumbo [3] and Gulfstream G-IV Aircraft [2]. Because of the advantages of SRAF technology, it is beneficial to broaden its applications to other areas, such as locomotive industry, where the panels normally have large size and complex shape. However, the current SRAF applications are for the panels with large size but relatively small curvatures, and most experimental and modelling investigations so far are mainly focused on the SRA behaviours of the age-hardenable aluminium alloys in the elastic region. Very few study has been done on SRAF of panels with large curvature, in which the material deformed in the plastic region. Yang [4] manufactured a singly-curved stiffened panel with a curvature radii of 650 mm, which is the largest curvature of the SRAFed panel published so far. The unavoidable springback phenomenon occurring during SRAF varies with curvature and thickness of the plate as well as the SRAF process parameters, and to accurately predict it for the formed plate, the development and calibration of the material model for the SRA behaviour is very important. Recently, some modelling work has been carried out to predict the stress-relaxation/creep ageing behaviours in both elastic and plastic regions [5, 6] and both explicit and implicit algorithms have been used in previous studies on FE simulations of the SRAF process of aluminium alloys [7-9]. However, no reports have been found on FE simulations and SRAF tests of panels with large and complex curvatures.

Aluminium alloy AA6082 is one of the most used lightweight materials in the locomotive industry due to its good combination of strength and weldability [10, 11]. To broaden SRAF to the panels with large and complex curvatures in the locomotive industry, experimental investigation has been carried out on SRA behaviour of AA6082-T6 with initial loading in both the elastic and plastic regions [12]. The aim of the study is to use FE simulation to guide the tool surface design for manufacturing a component with complex and large curvature. An FE model is built to simulate the SRA behaviour of AA6082-T6 during SRAF for the first time at various stress levels ranging from elastic to plastic regions. An explicit integration method has been used to solve a constitutive material model and implemented into ABAQUS for FE simulation of the SRAF process. The techniques and procedures for implementation of the developed material model into ABAQUS are described in detail. The FE simulation has been carried out to determine the tool surface for SRAF of a panel with large and complex curvatures that was selected from an in-service high-speed train. The corresponding SRAF test has then been performed to validate the developed FE models in the prediction of springback behaviour during SRAF of the material. The hardness test of the specimens cut from the SRAFed plate has also been carried out to verify the post-form strength predicted by FE model.

2. FE simulation

2.1. Material model

SRA behaviour in both the elastic and plastic regions of AA6082-T6 has been investigated at 160 °C up to 12 hrs in an earlier study [12], during which there is no significant change in the yield strength within the time frame, which is important for the application of SRAF of peak-aged material. It was concluded that the enhanced stress relaxation with higher initial strains in the plastic region is mainly due to increased dislocation movement and decreased resistance of the material to stress relaxation deformation. Based on the analysis, the following set of constitutive equations has been employed for the prediction of the stress-relaxation ageing behaviour of AA6082-T6 from elastic to plastic regions:

$$\dot{\sigma} = E\dot{\epsilon}_e = -E\dot{\epsilon}_c \quad (1)$$

$$\dot{\epsilon}_c = A_1 \sinh\{B_1[(\sigma - \sigma_{th})(1 - \bar{\rho})]\} \text{sign}\{\sigma\} + k_4 \dot{\sigma}_{dis} \quad (2)$$

$$\sigma_{th} = C_{th} \bar{\lambda}^{-1} - C_1 \bar{\rho}^{n_4} \quad (3)$$

$$\dot{\bar{\rho}} = A_3(1 - \bar{\rho})|\dot{\epsilon}_c|^{n_1} - C_p \bar{\rho}^{m_4} \quad (4)$$

$$\dot{\bar{l}} = C_L(Q - \bar{l})^{m_2}(1 + \gamma_0 \bar{\rho}^{m_3}) \quad (5)$$

$$\dot{\bar{\lambda}} = k_3 \dot{\bar{l}} \quad (6)$$

$$\sigma_y = \sigma_{ss} + \sqrt{\sigma_A^2 + \sigma_{dis}^2} \quad (7)$$

$$\dot{\sigma}_{ss} = 0 \quad (8)$$

$$\dot{\sigma}_A = C_A(1 - \bar{l})\dot{\bar{l}}^{m_1} \quad (9)$$

$$\dot{\sigma}_{dis} = A_2 n_3 \bar{\rho}^{n_3-1} \dot{\bar{\rho}} \quad (10)$$

where $A_1, A_3, B_1, C_p, C_A, C_L, C_{th}, k_3, k_4, m_1, m_2, m_3, m_4, n_1, n_4, Q, \gamma_0, C_1$ are material constants to be determined from experimental data.

Eq. (1) is the relationship between the creep strain rate $\dot{\epsilon}_c$ and stress relaxation rate $\dot{\sigma}$, E is the Young's modulus of the material. Eq. (2) describes the evolution of creep strain rate $\dot{\epsilon}_c$, which is a function of applied stress σ , threshold stress σ_{th} , and normalised dislocation density $\bar{\rho}$; and annealing effect on recovery has also been added since greater effect occurs due to the existence of non-shearable precipitates [13-15]. Eq. (3) describes the evolution of threshold stress σ_{th} , which is a function of normalised inter-particle spacing $\bar{\lambda}$ and normalised dislocation density $\bar{\rho}$ [16, 17]. Eq. (4) describes the evolution of normalised dislocation density $\bar{\rho}$, which is defined as $\bar{\rho} = (\rho - \rho_i)/\rho_s$ where ρ is the instantaneous dislocation density, ρ_i is the dislocation density in the as-received material before loading, and ρ_s is the saturated dislocation density during stress-relaxation ageing [18]. Eq. (5) describes the evolution of precipitate size [8], where the normalised precipitate length $\bar{l}$ is used to represent, which is defined as $\bar{l} = l/l_p$ where l is the instantaneous precipitate length and l_p is the precipitate length at the peak-ageing condition, and thus $\bar{l}$ will evolve with an initial value of 1. The use of precipitate length is mainly due to the precipitation coarsening direction is along its length direction during SRA of AA6082-T6 at 160 °C up to 12 hrs [12]. Eq. (6) describes the evolution of the normalised inter-particle spacing, which is defined as $\bar{\lambda} = \lambda/\lambda_p$ where λ is the instantaneous inter-particle spacing and λ_p is the inter-particle spacing in the peak-ageing condition. $\bar{\lambda}$ will evolve with an initial value of 1 and follow a similar trend as $\bar{l}$. Eq. (7) describes the evolution of yield strength σ_y , which is a function of solution hardening σ_{ss} , precipitation hardening σ_A , and dislocation hardening σ_{dis} . The evolution of these three strength components are described in Eqs. (8-10) respectively. The initial state of the studied material is as peak-aged condition, the solutes concentration and volume fraction of the precipitates will change little during further ageing, and thus the strength comes from solute hardening is a constant as shown in Eq. (8) [19, 20].

Since a large number of dislocations has been generated during loading to the plastic region, the initial value of the normalised dislocation density is no longer 0, and so are the initial dislocation hardening strength and threshold stress. The equations to model their initial value are summarised in Eqs. (11 - 13) respectively [21].

$$\bar{\rho}_0 = k_2 \epsilon_0^{n_2} H(\sigma_0 - \sigma_y) \quad (11)$$

$$\sigma_{dis0} = A_2 \cdot \bar{\rho}_0^{n_3} \quad (12)$$

$$\sigma_{th0} = B_2 - k_1 \cdot \sqrt{\bar{\rho}_0} \quad (13)$$

where $k_2, n_2, A_2, n_3, B_2, k_1$ are material constants to be determined from experimental data. $H(\sigma_0 - \sigma_y)$ in Eq. (11) is the Heaviside step function; when $\sigma_0 \geq \sigma_y$, $H(\sigma_0 - \sigma_y) = 1$, representing the dislocation densities generated by loading in the plastic region. Otherwise, $H(\sigma_0 - \sigma_y) = 0$. Material constants in the equation were determined by fitting the simulated curves to the corresponding experimental results, and the determined material constants are listed in Table 1. Fig. 1 compares the computed results with experiments for stress-relaxation behaviour of AA6082-T6 under different initial strain levels ranging from elastic (0.25%, 0.30%, 0.35%) to plastic regions (0.80%, 1.20%, and 2.00%), and good agreement between them has been achieved. Additionally, 75%-90% of the total stress relaxation has taken place in the first 5 hr ageing process at all tested initial strain levels, and thus the ageing time of the SRAF test performed in this work is determined to be 5 hr for a better production efficiency.

Table 1 Summary of the calibrated material constants of the material model for stress-relaxation ageing of AA6082-T6 at 160 °C

A_1 (-)	A_2 (MPa)	A_3 (h^{-1})	B_1 (MPa)	k_3 (-)	C_p (-)	C_A (MPa)	n_4 (-)
3.1e-6	80	120	0.0685	3.355	0.0645	3	2
k_2 (-)	k_1 (MPa)	C_{th} (MPa)	B_2 (MPa)	m_1 (-)	m_2 (-)	C_1 (MPa)	m_4 (-)
12	190	31	95	0.3	2	0.2	0.1
n_1 (-)	n_2 (-)	n_3 (-)	C_L (h^{-1})	Q (-)	γ_0 (-)	k_4 (MPa $^{-1}$)	m_3 (-)
0.6	1.15	1	0.07	2.1	6	0.3	5

2.2. Implementation of material model

The developed material model is implemented into the commercial FE solver ABAQUS via the user-defined subroutine CREEP for process simulation. Both explicit and implicit methods have been used in previous studies on FE simulations of the SRAF process of aluminium alloys [7, 22], and the explicit method has been found to be more straightforward and convenient to use, with satisfying results. Therefore, the explicit integration algorithms are used in this work, and all the material constants and initial values are defined in the subroutine. The effectiveness of the developed FE model has been validated by stress-relaxation age forming (SRAF) of a singly-curved plate, which deformed in the plastic region with a curvature radius of 700 mm.

Fig. 1 Comparison of stress-relaxation curves between experiments (symbols) and calibrated models (solid lines) with six initial strain levels in (a) elastic and (b) plastic regions

The FE model created to simulate the SRAF process of an AA6082-T6 panel with large and complex curvatures is shown in Fig. 2, with the dimension of the objective shape and developed FE model for demonstration plate. The length and width of both upper and bottom tools in this model are respectively 800 and 280 mm. The blank is modelled with shell elements (S4R) in ABAQUS with a dimension of 800*300*3 mm. The penalty friction formulation is used, and the friction coefficient between the tool and the blank is defined as 0.1 [4]. In order to obtain satisfactory results in a more efficient way, the mesh convergence tests have been performed, the results were obtained with different blank mesh size, i.e., 5, 10, 20, 25 mm. The maximum vertical deflections at $x = 0$ on the plate by using different mesh sizes are plotted in Fig. 3. From the point of view of efficiency and

computational time, 10 mm was selected as the mesh size of the blank. The basic mesh properties of the model are summarised in Table 2.

(a) Dimension of the objective shape

(b) Isometric view of the developed FE model

Fig. 2 FE model for SRAF: (a) Dimension of the objective shape (b) Isometric view of the developed model

Fig. 3 Mesh convergence test results

Table 2 Basic mesh properties of each part in FE model for the panel

Part name	Element type	Element number	Mesh size (mm)
Upper tool	Discrete rigid (R3D4)	9760	5
Bottom tool	Discrete rigid (R3D4)	9760	5
Blank	Shell (S4R)	2400	10

For easier implementation of FE model, the whole SRAF process is regarded as an isothermal process and the heating and cooling process are not taken into account since their durations are relatively short compared to the ageing process. Also, due to the slower creep deformation at lower temperature, and a minor effect of different stress levels on ageing behaviour of the material in this study, the thermal effects are ignored in the FE modelling in this study. Therefore, the stress-strain relationship of AA6082-T6 at the ageing temperature 160 °C is used to simulate the material properties evolution during loading in SRAF FE simulations in this study. A Young's modulus of 70 GPa and Poisson's ratio of 0.33 is defined for the elastic property of the material. The plastic part of the experimental stress strain curve is inputted into the FE models to define the plastic properties of the material, and the inputted initial plastic strain ($\epsilon_p=0$) is defined at the point $\epsilon = \sigma/E$.

The numerical simulation of SRAF tests has been divided into five stages according to practical SRAF procedures, including:

- 1) Initial stage: define the reference points of the upper and bottom forming tools. The bottom tool is fully constrained, and the upper tool can only move along its thickness direction. The blank is positioned close to the bottom tool at initial stage.
- 2) Gravity stage: position the tools and blank in the FE model automatically through a gravity stage simulation.
- 3) Loading stage: apply a predetermined displacement along the thickness direction to fully load the upper tool onto the blank.
- 4) Stress-relaxation ageing stage: hold all the parts for a controlled time, for example 5 hrs in this study, during which the creep subroutine is activated, and the stress-relaxation ageing behaviour of the blank is simulated.
- 5) Unloading stage: the upper tool is set to lift to its original location, and the springback of the blank occurs.

The setting of boundary conditions is quite rigorous because of the large and complex deformations needed for the objective shape. The commonly accepted three-node boundary condition setting has been used, and the first node is selected as the first point on the blank contacted with the upper tool during loading, and the other two nodes are selected with the same x or y coordinates as the first node respectively in y - and x - directions to control the translational and rotational movement of the blank.

Due to the difficulty in accurately predicting the springback of the panels after forming, especially for those with large and complex curvatures, springback compensation is an essential step in the tool shape determination process. Generally, springback is compensated by adding the dimensional difference between the objective shape and FE simulated shape of the formed blank to the tool shape used for the last simulation and generating a new tool shape to be used in next simulation. An accelerated springback compensation method has been used in this study, and more details of the method can be found in an earlier study [23]. The optimised tool shape for producing the demonstration panel was obtained after 3 iterations of springback compensation that the maximum error between the formed shape by the optimised tool and the objective shape was controlled less than 2 mm.

2.3. Simulation results

Fig. 4 shows the effective stress distribution in the blank after each stage during SRAF by using the optimised tools. The maximum effective stress in the loaded blank was around 229 MPa, which already reaches the plastic region at 160 °C; the minimum effective stress in the blank was around 32 MPa; and the effective stress in most of the loaded blank was in the range of 200-230 MPa. After 5 hr stress-relaxation, the majority of the effective stresses decreased to around 160 MPa, with a maximum value of 175 MPa and a minimum value of 17 MPa. After fully unloading, the residual stresses left in the blank were mainly in the range of 3-150 MPa, and higher residual stresses were observed at the locations with larger curvatures.

Fig. 4 Numerical results of the effective stress distribution in the blank after each stage during SRAF of the panel

Fig. 5 shows the simulated effective plastic strain generated after the loading stage of the SRAF process, and a maximum plastic strain of around 5.5% was achieved after loading.

Fig. 5 FE simulated effective plastic strain of the panel after loading

Creep strain was generated during stress-relaxation, and its evolution with ageing time is shown in Fig. 6, with gradual increase in ageing time. The maximum creep strain generated during stress-relaxation was less than 3% of the maximum plastic strain value during the loading stage, indicating the significant effect of the initial plastic strain on the final shape of the SRAFed workpiece.

Fig. 6 Evolution of the FE simulated creep strain of the panel during stress-relaxation ageing

The resultant yield strength of the SRAFed panel at room temperature was predicted to be in the range of 285.5-295 MPa as shown in Fig. 7, with insignificant variation of yield strength of the SRAFed material compared to its initial state which was set as 290 MPa based on the material model.

Fig. 7 FE simulated yield strength of the panel after unloading

3. SRAF test verification

SRAF tests were performed using a flexible forming tool with multi forming pins, as detailed in an earlier study [24]. Fig. 8 shows the toolset for SRAF test. The height of each forming pin was determined according to the optimised tool shape, and the blank was prepared with a dimension of 820*300*3 mm³. The blank was firstly loaded to fully contact with the top and bottom pins of the forming tool, so that it be deformed to the predetermined shape of the tool surface. The tools were tightened and the whole tool set was moved into a pre-heated furnace. The 5 hr SRA was started once the blank reached 160 °C. After the 5 hr SRA process, the tool set was moved out of furnace and unloaded. A 3D coordinate measurement machine CMM LKG90C was employed to measure the deflections of the SRAFed blank.

Fig. 8 Views of tool setup for SRAF test

Fig. 9 shows the measured deflections of SRAFed panel (symbols) at selected locations and the results obtained from the FE model (dashed lines) and the objective shape (solid lines). As can be seen, a very good agreement has been achieved among these three sets of data. The maximum deviation among them is within 4 mm, which is less than 5% of the total deflection of the panel and fulfils the general dimensional accuracy requirement for panel assembling in industry. These deviations may come from the limitations of the lab-scale flexible tool currently used, that the flexible pins are not close enough to generate exactly some specific, large curvature. Such deviations can be further decreased by using the tool with more forming pins or even using solid tools.

Fig. 9 Comparison of the formed shape along the z -direction by using the optimised tool from experiments (symbols) and FE simulation results (dashed lines) with the objective shape (solid lines) of the demonstration panel at cross-sections with the indicated x position

The strength of the SRAFed material was evaluated by the hardness test, using Zwick hardness tester with 30 N load (HV3). Six samples were cut from the as-received plate and the SRAFed plate respectively, five tests for each sample, and the hardness results are shown in Fig. 10, including their variations. It was found that the average hardness decreased from 195.2 ± 9 HV3 to 185.2 ± 5 HV3 after 5 hr SRA at 160 °C. The results correspond well with the simulated results that the SRA process contribute insignificant effect to the strength evolution of AA6082-T6 during SRAF. The current study also shows that sufficient strength has been maintained after SRAF and is adequate for industrial application.

Fig. 10 Hardness results of the as-received and the SRAFed plates

4. Conclusions

Finite element simulation has been carried out on stress-relaxation age forming of AA6082-T6 for a component ($820 \times 300 \times 3$ mm³) with complex and large curvatures. The evolutions of the stress and strain distributions and mechanical property of the blank during SRAF have been predicted by FE simulations. An optimised tool surface was obtained through springback compensation and was used to carry out corresponding SRAF of an AA6082-T6 panel for verification. It was found that the maximum creep strain generated during stress-relaxation was less than 3% of the maximum value of the plastic strain during the loading stage, showing the very significant effect of the initial plastic strain on the final shape of for components with large curvature. It was also observed that less springback occurred at the locations with larger curvatures. The successful manufacture of the industrial panel with a maximum shape error of 4 mm, and the correct prediction of minor change in the strength/hardness of the SRAFed plate compared to the as-received plate, have proven the feasibility and the accuracy of the developed modelling and springback compensation techniques. It also shows the importance of FE simulation to guide the tool surface design. The work in this study provides a series of numerical and manufacturing tools for SRAF process of AA6082-T6, which can be applied to other heat treatable aluminium alloys and guide further industrial manufacturing of panels with complex and large curvatures through SRAF technology.

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