An accelerated springback compensation method for creep age forming

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Received: 1 August 2018 / Accepted: 11 December 2018 / Published online: 26 December 2018
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Abstract

Springback compensation is essential for tool design in creep age forming (CAF) process. In this study, a new accelerated springback compensation method integrating springback mechanism of a plate with creep-ageing behaviour of materials has been developed for CAF tool design to manufacture both singly and varyingly curved products. Springback compensation curves that relate the objective shapes and springback compensated shapes by their curvature, stress and strain states have been established, based on the numerical solution of springback behaviour of CAF process. For singly curved products, a one-step springback compensation method is proposed with reference to the springback compensation curves, and its effectiveness has been demonstrated by CAF test with a peak-aged aluminium alloy AA6082-T6. For products with varying curvatures, an accelerated method is developed for CAF tool design by integrating springback compensation curves with finite element (FE) assisted displacement adjustment techniques. The new accelerated method can significantly improve the tool design efficiency for CAF process when compared with conventional displacement adjustment techniques and has been verified by CAF manufacture of a varyingly curved product with AA6082-T6 material. The new accelerated springback compensation method developed in this study can be used for efficient tool design for CAF process of various products.

Keywords Creep age forming · Springback compensation · Displacement adjustment · Tool design · Stress-relaxation · AA6082-T6

Nomenclatures

C^0, C^i, C^{i+1}	Initial tool shape, and updated tool shapes at i^{th} and $(i+1)^{\text{th}}$ iterations	$k_0, k_1, \Delta k$	Curvatures of plate after loading and after springback, and curvature change during unloading (mm^{-1})
O	Shape of objective product	k_a, k_b	Curvatures of objective shape and corresponding optimised tool shape after springback compensation respectively (mm^{-1})
E	Young's modulus (GPa)	$\bar{L}$	Normalised precipitate length
E^i	Shape error between objective and formed shape at i^{th} iteration	M_0, M_1, M_2	Bending moments in plate after loading, stress-relaxation and unloading respectively (N m)
e_σ	Maximum effective stress difference allowed for convergence (MPa)	R_0	Radius of plate after loading (mm)
F^i	Springforward force distribution at i^{th} iteration	S^i	Formed shape at i^{th} iteration
h	Plate thickness (mm)	Sp	Springback ratio of plate in CAF
I	Second moment of area (m^4)	W	Strain energy per unit volume for rubber material (J m^{-3})
J_1	First deviatoric strain invariant for rubber material	z	Distance to the neutral plane (mm)
		α, α^i	Compensation factor and its value at i^{th} iteration
		$\bar{\rho}$	Normalised dislocation density
		$\varepsilon_a, \varepsilon_b$	Strains of objective shape and corresponding optimised tool shape

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	after springback compensation respectively
$\varepsilon_{c1}, \varepsilon_{e1}$	Creep strain and remaining elastic strain in the plate during stress-relaxation
$\varepsilon_{t0}, \varepsilon_{p0}$	Total strain and plastic strain in the plate after loading to tool shape
$\varepsilon'_{t0}, \varepsilon'_e$	Total strain and effective strain in the plate loaded to objective shape respectively
$\varepsilon_{e-max}, \varepsilon'_{e-max}$	Maximum effective strains in the plate loaded to tool shape and objective shape respectively
σ_a, σ_b	Stress of objective shape and corresponding optimised tool shape after springback compensation respectively (MPa)
$\sigma_A, \sigma_{dis}, \sigma_{ss}$	Strength contributions from precipitates, dislocations and solid solution respectively (MPa)
σ_0, σ_1	Stresses in the plate after loading and stress-relaxation respectively (MPa)
σ'_0, σ'_e	Stress and effective stress in the plate loaded to objective shape respectively (MPa)
$\sigma_{e-max}, \sigma'_{e-max}$	Maximum effective stresses in the plate loaded to tool shape and objective shape respectively (MPa)
$\sigma^i_{e-max}, \sigma^{i-1}_{e-max}, \sigma^{i+1}_{e-max}$	Maximum effective stresses in the plate loaded to tool shape at i^{th} , $(i-1)^{th}$ and $(i+1)^{th}$ iterations (MPa)
σ_y	Yield strength (MPa)

1 Introduction

Creep age forming (CAF) is a forming technology for manufacturing large/extra-large panels with heat-treatable aluminium alloys and has been widely applied in aerospace industry, such as wing skin panels [1]. The process is comprised of three main stages: 1) loading aluminium alloy plate to tool shape; 2) heating the whole tool setup to an artificial ageing temperature and holding for a specific time, during which age hardening and stress-relaxation occur to concurrently strengthen and deform the plate and 3) unloading. As only part of the stress in the loaded plate can be relaxed by stress-relaxation, large springback generally occurs after unloading [2]. Hence, a springback compensation method for tool design is essential for CAF applications.

Springback can be considered as an elastic recovery occurred during unloading [3] and has a significant effect on dimensions of formed products in many sheet metal forming processes, such as deep drawing [4], stretch-bending [5] and hydroforming [6]. Both analytical and finite element (FE) methods have been used to predict springback for various metal forming processes, which have been reviewed by

Wagoner et al. [7]. In order to manufacture products with desired accuracy, the recovered deformation from springback needs to be compensated to the objective shape for tool design. As springback behaviour is highly non-linear, iterative strategy is generally used for tool design [7]. Two springback compensation methods, springforward (SF) method and displacement adjustment (DA) method, have been developed and widely applied in metal forming processes.

SF method was initially developed by Karafillis and Boyce [8]. Figure 1 shows basic procedures of the method, which uses the “springforward” force to iteratively update tool shapes. The tool shape at the first iteration is set as the objective shape. In each iteration, the tool shape is updated by applying the “springforward” force (F^i), which has been recorded by loading the prepared blank to the tool shape in previous iteration, to the objective shape. The method can be expressed by the following function:

$$C^{i+1} = g(O, F^i) \quad (1)$$

where C^{i+1} represents the tool shape updated for next iteration and O represents the objective shape. F^i can be obtained by either analytical or FE modelling methods. The optimised tool shape is obtained when the shape error between the formed shape (S^{i+1}) and objective shape ($E^{i+1} = |S^{i+1} - O|$) fulfils related requirements. The effectiveness and efficiency of the method have been evaluated by some axisymmetric 3-D cases [9]. Some variations of this method have been proposed and achieved a higher convergence efficiency than the original one, by decomposing the internal force into an internal membrane force and a bending moment [10] or involving a scalar multiplier α to the internal forces in Eq. (1), as αF^i [11]. However, further research [12] indicated that the convergence of the method is hard to achieve when dealing with asymmetrical products with complex shapes.

DA method, originally proposed by Gan et al. [13], updates tool shapes by adding springback resulted shape errors in previous iteration to the tool shape, as schematically shown in Fig. 1. Each iteration can be expressed as below:

$$C^{i+1} = C^i - (S^i - O) \quad (2)$$

where C^i and C^{i+1} are tool shapes in current and next iterations and S^i represents the formed shape in the current iteration, which can be obtained through FE simulations. The initial tool shape is set as the objective shape (O). The theory behind DA method under simple stretch-bending conditions has been explained by Lingbeek et al. [14]. Although the mechanism base of this method is comparatively weaker than SF method, as indicated by Cheng et al. [15], the method has been widely used in both research and industries for metal forming processes due to its simplicity in applications, even for asymmetrical products with complex shapes [16].

Fig. 1 Schematic of springforward (SF) and displacement adjustment (DA) methods for springback compensation

A number of variations of DA method have been proposed for some forming processes to improve its convergence efficiency. Yang and Ruan [17] investigated the effect of shape error directions on efficiency of the method, e.g., vertical, actual or normal directions, and proposed a comprehensive compensation method to optimise the direction and accelerate the compensation speed. A scalar α was also proposed to multiply the shape error in Eq. (2) to improve the convergence efficiency, as $\alpha(S^i - O)$; however, it is still a challenge to determine a reasonable α value for different forming processes [18]. Some new methods were also proposed by combining DA method with surface construction method [19], to improve the capability of the method in tool design for more complicated products.

For CAF process, material constitutive models and FE simulation models for various aluminium alloys, e.g., Al–Cu–Mg [20], Al–Zn–Mg [21], Al–Cu–Li [22] and Al–Mg–Si [23], have been well developed to achieve high precision springback prediction. Conventional DA method assisted by FE simulation is applicable for tool design in CAF process, but will suffer from the low convergence speed. In DA method, the initial tool is set as the objective shape (O) of CAF products, which generally have only slight deformation after loading and thus very high springback, up to 80–90%, occurs [1]. In addition, the shape error ($S^i - O$ in Eq. (2)) compensated in each iteration is also very small, resulting in the low efficiency for CAF springback compensation [24]. Few studies have investigated springback compensation method for CAF process. Xu et al. [25] studied a springback compensation case for CAF of large aluminium alloy plates based on DA method. Different compensation factors of α were tested; however, the theory of obtaining α was not given. Xiong et al. [26] proposed a rapid springback compensation method based on Quasi Newton algorithm, which shows better efficiency than DA method. The compensation displacement was obtained by solving a set of non-linear equations for each node,

rather than using the simple shape errors in DA method, which largely increases the complexity of the algorithm and may lead to convergence problems when applying to products with complex shapes.

In this study, a new springback compensation method based on springback mechanism of creep-aged material is proposed to accelerate the tool design procedures for CAF process. A numerical solution of springback behaviour has been developed for CAF of singly curved products and springback compensation curves relating main properties between plates before and after springback have been established. Based on these curves, a one-step method has been proposed for tool design in CAF of singly curved products. An accelerated displacement adjustment (ADA) method integrating springback compensation curves with FE simulations has been developed for tool design in CAF process of varyingly curved products. The effectiveness and high efficiency of the methods for CAF tool design have been demonstrated and verified by CAF of a heat treatable aluminium alloy, AA6082-T6.

2 Springback properties of CAF process

2.1 Springback mechanism of CAF

Springback occurs in the unloading stage of CAF because of the elastic recovery from the release of residual stresses in the aluminium alloy plate after stress-relaxation. Figure 2 illustrates the stress and strain evolutions during loading, stress-relaxation, and unloading stages of CAF for both elastically and plastically loaded conditions. Under the elastically loaded condition (Fig. 2a), the applied stress σ_0 will be relaxed to σ_1 after stress-relaxation, and σ_1 will then be released in the subsequent unloading stage, leading to the springback related elastic strain recovery (ε_{e1}).

Fig. 2 Schematic showing springback mechanism in (a) elastic and (b) plastic regions

Under the plastically loaded condition, springback occurs with the same mechanism. The only difference is that initial plastic strain (ε_{p0}) will be generated in the loading stage, as shown in Fig. 2b.

The detailed stress and strain evolutions during CAF and corresponding springback behaviour are schematically analysed through CAF of an aluminium alloy plate with a singly curved shape. Figure 3a shows the shape of test plate at initial, loaded and CAFed states and Fig. 3b illustrates the stress and strain distributions through thickness of the test plate after loading and after stress-relaxation.

After loading to a singly curved shape with a uniform radius of R_0 , the total strain distributed through thickness of the plate is:

$$\varepsilon_{r0}(z) = -z \cdot k_0, \quad \left(-\frac{h}{2} \leq z \leq \frac{h}{2}\right) \quad (3)$$

where $k_0 = 1/R_0$ is the curvature of the loaded shape, h is the thickness of the plate and z is the distance to the neutral plane through thickness of the plate, ranging from $-h/2$ to $h/2$. If the plate is elastically loaded, corresponding stress distribution is:

$$\sigma_0(z) = E \cdot \varepsilon_{r0}(z), \quad \left(-\frac{h}{2} \leq z \leq \frac{h}{2}\right) \quad (4)$$

where E is the Young's modulus of the alloy. If the plate is plastically loaded, the stress distribution through thickness of the plate is [27]:

$$\begin{cases} \sigma_0(z) = E \cdot \varepsilon_{r0}(z), & \left(-\frac{\sigma_y}{Ek_0} \leq z \leq \frac{\sigma_y}{Ek_0}\right) \\ \sigma_0(z) = f(\varepsilon_{p0}(z)), & \left(-\frac{h}{2} \leq z < -\frac{\sigma_y}{Ek_0} \text{ or } \frac{\sigma_y}{Ek_0} < z \leq \frac{h}{2}\right) \end{cases} \quad (5)$$

where $f(\varepsilon_{p0}(z))$ is a function describes the hardening rule of the alloy in the plastic area. The power-law equation is the most common one [28] and is used in this study. The corresponding plastic strain in the plate after loading then can be obtained as:

$$\begin{cases} \varepsilon_{p0}(z) = \varepsilon_{r0}(z) + \frac{\sigma_y}{Ek_0}, & \left(\frac{\sigma_y}{Ek_0} < z \leq \frac{h}{2}\right) \\ \varepsilon_{p0}(z) = \varepsilon_{r0}(z) - \frac{\sigma_y}{Ek_0}, & \left(-\frac{h}{2} \leq z < -\frac{\sigma_y}{Ek_0}\right) \end{cases} \quad (6)$$

Fig. 3 Schematic showing a initial shape, loaded shape and CAFed shape after springback and b stress and strain distributions along half thickness of the test plate after loading (solid line) and stress-relaxation (dashed line)

After the stress-relaxation stage of CAF, part of the loaded stress will be relaxed and some elastic strains will be converted to creep strains. The creep-ageing/stress-relaxation behaviour of various aluminium alloys has been investigated and modelled by some previous studies [20, 21]. It can be concluded that creep strain (ε_{c1}) generated during stress-relaxation is mainly determined by the stress-relaxation time t and applied stress level $\sigma_0(z)$ for a particular material, as:

$$\varepsilon_{c1}(z) = F(t, \sigma_0(z)) \quad (7)$$

As demonstrated in Fig. 2, the remaining elastic strain in the plate after stress-relaxation is [1]:

$$\varepsilon_{e1}(z) = \varepsilon_{t0}(z) - \varepsilon_{p0}(z) - \varepsilon_{c1}(z) \quad (8)$$

The remaining stress after stress-relaxation and corresponding moment in the plate are:

$$\sigma_1(z) = E\varepsilon_{e1}(z) \quad (9)$$

$$M_1 = \int_{-h/2}^{h/2} \sigma_1(z) * z * dz \quad (10)$$

In the unloading stage, all constraints in the plate will be removed and the total moment in the plate after stress relaxation will be fully released, leading to springback of the CAFed plate [29]. The changed curvature of the plate during the unloading stage is determined by the released total moment and can be calculated as:

$$\Delta k = \frac{M_2 - M_1}{EI} = -\frac{M_1}{EI} \quad (11)$$

where $M_2 = 0$ is the moment in the plate after unloading and I is the second moment of area of the plate. Hence, the final curvature of CAFed plate after springback is:

$$k_1 = k_0 + \Delta k \quad (12)$$

A springback ratio (Sp) is introduced to represent the springback level of the plate after CAF:

$$Sp = \frac{k_0 - k_1}{k_0} \quad (13)$$

$Sp = 0$ represents no springback and $Sp = 1$ means full springback, i.e., all deformation has been recovered elastically after CAF. Hence, springback level of the plate in CAF process is mainly determined by stress-relaxation behaviour of the material, applied stress/strain conditions and stress-relaxation time according to Eqs. (3)–(13).

2.2 Springback behaviour of CAF

In order to acquire the detailed springback behaviour of a particular aluminium alloy according to the springback mechanism presented in the previous section, a constitutive model

for creep strain evolution during CAF (Eq. (7)) is required. Many creep-ageing constitutive models have been proposed for different aluminium alloys, such as Al–Zn–Mg [21], Al–Cu–Mg [30] and Al–Mg–Si [23] alloys, which can be directly used to replace Eq. (7) in Section 2.1 for springback behaviour calculations for CAF of corresponding alloys. In this study, one of the heat treatable Al–Mg–Si alloys, AA6082 with a peak-aged initial temper T6, was selected to demonstrate the springback behaviour calculation and its application for springback compensation for CAF tool design in subsequent sections. The stress-relaxation behaviour and corresponding constitutive modelling for AA6082-T6 at 160 °C have been investigated previously, and the unified constitutive model is listed below [23]:

$$\dot{\varepsilon}_{c1} = A_1 \sinh \left\{ B_1 \left[|\sigma_0| \left(1 - \bar{\rho} \right) - k\sigma_y \right] \right\} \text{sign} \{ \sigma_0 \} \quad (14)$$

$$\dot{\bar{\rho}} = A_3 \left(1 - \bar{\rho} \right) \left| \dot{\varepsilon}_{cr} \right| - C_p \bar{\rho}^{m_4} \quad (15)$$

$$\dot{\sigma}_A = C_A \left(1 - \bar{L} \right) \bar{L}^{m_1} \quad (16)$$

$$\bar{L} = C_r \left(Q - \bar{L} \right)^{m_2} \left(1 + \gamma_0 \bar{\rho}^{m_3} \right) \quad (17)$$

$$\dot{\sigma}_{dis} = A_2 n \bar{\rho}^{n-1} \dot{\bar{\rho}} \quad (18)$$

$$\dot{\sigma}_{ss} = 0 \quad (19)$$

$$\sigma_y = \sigma_{ss} + \sqrt{\sigma_A^2 + \sigma_{dis}^2} \quad (20)$$

$$\sigma_0 = E \left(\varepsilon_{t0} - \varepsilon_{p0} - \varepsilon_{c1} \right) \quad (21)$$

where normalised dislocation density ($\bar{\rho}$) and normalised precipitate length ($\bar{L}$) are main microstructural parameters that determine creep strain (ε_{c1}) and yield strength (σ_y) evolutions during CAF. Yield strength of the material is contributed by three strength components: age hardening (σ_A), solid solutes hardening (σ_{ss}) and dislocation hardening (σ_{dis}). Initial values of the process variables are listed in Table 1. $A_1, B_1, k, C_A, m_1, C_r, Q, m_2, \gamma_0, m_3, A_2, n, A_3, C_p$ and m_4 are material constants and are also listed in Table 1 [23].

Additionally, the power-law equation is used to characterise the hardening rule for the material and implemented into Eq. (5), as.

$$\sigma_0(z) = f(\varepsilon_{p0}(z)) = \sigma_y + K \varepsilon_{p0}^m(z) \quad (22)$$

where σ_y is the yield strength of the material and K and m are material constants. For the AA6082-T6 alloy used in the current study, $\sigma_y = 290$ MPa, $K = 151.1$ MPa and $m = 0.684$ according to the stress-strain curve of the material.

By implementing the CAF constitutive model and power-law equation into Eqs. (3)–(13) and solving the equations by explicit integration, springback behaviour of AA6082-T6 plate with 4 mm thickness after CAF for 3 h at 160 °C were

Table 1 Initial values of process variables and material constants for CAF of AA6082-T6 at 160 °C

A_1 (h^{-1})	B_1 (MPa)	k (–)	C_A (MPa)	m_1 (–)	C_r (–)	Q (–)	m_2 (–)	γ_0 (–)	m_3 (–)
$4.2\text{e-}5$	0.0525	0.375	0.4	0.5	0.03	10	1.4	1.5	1.4
A_2 (MPa)	n (–)	A_3 (–)	C_p (–)	m_4 (–)	σ_{A0} (MPa)	σ_{ss0} (MPa)	σ_{dis0} (MPa)	$\bar{L}_0$ (–)	$\bar{\rho}_0$ (–)
140	0.54	550	0.035	1.1	150	140	0	1	1E-5

obtained. Figure 4 shows variation of springback ratio with different total strain levels after loading. A very high level of springback ratio is observed in the elastic region, with the lowest value of 0.74 at the yield point. In the plastically loaded area, the springback ratio decreases continuously with increasing total strain and it is expected to converge to 0 eventually. In addition, when the total applied strain is lower than a particular level (0.165% for AA6082-T6 at 160 °C), springback ratio nearly equals to 1, which indicates that nearly all deformation is recovered elastically. This is due to a threshold stress that exists for creep of material, below which no creep occurs [31]. Hence, there is a no creep zone in Fig. 4 when $\varepsilon_{t0} < 0.165\%$.

3 The accelerated springback compensation method for CAF applications

3.1 One-step method for singly curved products

The relationships between the key parameters, such as curvature, strain and stress, in loaded singly curved plate and corresponding formed plate after springback in CAF process can be quantitatively obtained according to Eqs. (3) to (23). For example, for a loaded singly curved plate with a curvature of k_0 , the corresponding curvature of the CAFed plate k_1 can be calculated according Eq. (12), in which Δk is determined by the remained stress (Eq. (9)) and moment (Eq. (10)) in the plate after stress-relaxation. The remained stress, in turn, can be calculated from the constitutive

Fig. 4 Springback ratio with different loaded total strain levels after CAF with 4 mm thick AA6082-T6 plate at 160 °C for 3 h

equations. Figure 5 shows the quantitative relationships for AA6082-T6 alloy after 1, 3 and 5 h CAF at 160 °C, which can act as the springback compensation curves for this material.

Figure 5a shows springback compensation curves for forming curvatures, which indicates that for a particular CAF case, a plate loaded with a uniform curvature of k_0 will be formed to have a curvature of k_1 after CAF. Based on the curves in Fig. 5a, one-step tool design for CAF of singly curved products can be achieved. For example, in order to manufacture a singly curved AA6082-T6 plate with a curvature $k_1 = k_a$ by 5 h CAF process at 160 °C, the tool shape should be designed to have a curvature $k_0 = k_b$, which can be directly obtained by the springback compensation curve (solid line) in Fig. 5a. With this method, tool shape of singly curved products in CAF can be determined by just one step.

Meanwhile, other springback compensation curves that indicate relationships between the surface stress or strain in test plates loaded to objective shape (σ'_0 or ε'_{t0}) and compensated tool shape (σ_0 or ε_{t0}) can also be plotted, as shown in Fig. 5b and c.

The springback compensation curves for 1, 3 and 5 h CAF of AA6082-T6 have been obtained and demonstrated in Fig. 5. With a longer CAF time, a higher curvature of k_1 can be formed after CAF with the same tool shape (k_0), as more creep strain is accumulated with longer CAF time, leading to a smaller springback ratio [2]. However, the stress-relaxation rate decreases with time [23] and there is a limit to the maximum k_1 for each k_0 . This is demonstrated by the much less increase of k_1 from 3 to 5 h compared with that from 1 to 3 h in Fig. 5a.

3.2 Accelerated displacement adjustment method for varying curved products

Most CAF products have shapes with varying curvatures, whose springback behaviour cannot be directly obtained by the proposed method for singly curved shapes in Section 2. The one-step springback compensation method is not applicable for CAF with these complicated cases. Conventional DA method suffers from the low convergence speed in CAF applications due to two main limitations: i) the initial tool is set as the objective shape of products ($\mathcal{O}$), which has only slight

Fig. 5 Springback compensation curves for key parameters of **a** curvature, **b** strain and **c** stress at the surface of test plate after 1 h (dotted lines), 3 h (dashed lines) and 5 h (solid lines) CAF with 4 mm thick AA6082-T6 plate at 160 °C

deformation and results in very high springback and ii) the shape error ($\mathbf{S}^i - \mathbf{O}$ in Eq. (2)) compensated in each iteration is too small when considering the high springback. Hence, an ADA method is developed for CAF applications combining springback compensation curves (Fig. 5) and FE-assisted DA methodology to overcome these two limitations.

The ADA method developed in this study is comprised of two steps: i) obtain the initial tool shape according to CAF springback compensation curves for the particular material, rather than using the objective shape in conventional DA method; ii) optimise the initial tool shape based on the DA methodology until the final product is formed with a satisfied accuracy.

At the first step, springback compensation curves, such as the ones illustrated in Fig. 5 for CAF of AA6082-T6, are used to determine the initial tool shape. The applied stresses (σ'_0 and σ_0) and strains (ϵ'_{t0} and ϵ_{t0}) in springback compensation curves (Fig. 5b and c respectively) can be replaced by corresponding effective stresses (σ'_e and σ_e) and strains (ϵ'_e and ϵ_e), as they are identical in the singly curved case. Either map of effective stress or effective strain then can be used to guide initial tool shape determination for CAF of products with complex shapes. As complicated distributions of effective stresses and strains are expected in the loaded plate with a complex shape, the maximum effective stress and strain in the loaded plate are selected to determine the initial tool shape, so as to simplify the method and at the same time avoid over

compensation. Similar to the one-step springback compensation method for singly curved products introduced in Section 3.1, the initial tool shape can be designed to have a maximum effective stress or strain in the loaded plate (e.g. $\sigma_{e-max} = \sigma_b$ or $\epsilon_{e-max} = \epsilon_b$), whose value has been determined by the maximum stress or strain in the plate loaded to the objective shape (e.g., $\sigma'_{e-max} = \sigma_a$ or $\epsilon'_{e-max} = \epsilon_a$) according to springback compensation curves in Figs. 5b or c. The DA methodology with a compensation factor α can be applied for the initial tool shape determination, as:

$$\mathbf{C}^0 = \alpha \mathbf{O} \quad (23)$$

where $\mathbf{C}^0$ is the designed initial tool shape, with which $\sigma_{e-max} = \sigma_b$ or $\epsilon_{e-max} = \epsilon_b$ is obtained as demonstrated above and $\mathbf{O}$ is the objective shape, with which $\sigma'_{e-max} = \sigma_a$ or $\epsilon'_{e-max} = \epsilon_a$ after loading, as illustrated in Fig. 5b or c for 5-h processing time. The same compensation factor α is used for the whole plate shape.

As the relationships between the maximum effective stresses or strains and the particular tool shapes for varyingly curved products cannot be directly calculated through analytical methods, the numerical secant method has been applied to iteratively obtain the compensation factor α in Eq. (23) until the required maximum effective stress or strain ($\sigma_{e-max} = \sigma_b$ or $\epsilon_{e-max} = \epsilon_b$ in Fig. 5b and c) has been achieved in the plate loaded to $\mathbf{C}^0$. The following expression is used to iteratively obtain α when the maximum effective stress is considered:

$$\alpha^{i+1} = \alpha^i - (\sigma_{e-\max}^i - \sigma_b) \frac{\alpha^i - \alpha^{i-1}}{\sigma_{e-\max}^i - \sigma_{e-\max}^{i-1}} \quad (24)$$

where α^{i+1} , α^i and α^{i-1} are respectively compensation factors for the $(i+1)^{\text{th}}$, i^{th} and $(i-1)^{\text{th}}$ iterations; $\sigma_{e-\max}^i$ and $\sigma_{e-\max}^{i-1}$ are the maximum effective stresses in the loaded plates with tool shapes in i^{th} and $(i-1)^{\text{th}}$ iterations, which can be obtained through FE simulation. Two initial points of α for the secant method were given as $\alpha^0 = 0$ and $\alpha^1 = 1$ and the compensation factor at subsequent iterations (α^i , $i \geq 2$) then can be obtained according to Eq. (24). The iterative strategies for conditions that α is within (black curve in Fig. 6) or out of (grey curve in Fig. 6) the range of the two initial points are illustrated in Fig. 6. The convergence criterion of the secant method is defined as:

$$|\sigma_b - \sigma_{e-\max}^{i+1}| < e_\sigma \quad (25)$$

where e_σ is the maximum effective stress difference allowed for convergence. When the difference between the maximum effective stress with the tool shape obtained in $(i+1)^{\text{th}}$ iteration ($\sigma_{e-\max}^{i+1}$) and the desired value for the objective product (σ_b) is within the convergence requirement (e_σ), the final compensation factor α can be achieved, as $\alpha = \alpha^{i+1}$.

With the obtained compensation factor α , CAF with the initial tool shape C^0 can be performed to obtain corresponding formed shape S^0 . If the maximum difference between the formed shape and the objective shape ($\max(S^0 - O)$) is within the required shape error e , this initial tool can be treated as the final optimised tool shape for CAF manufacture. Otherwise, the second step of the ADA method needs to be carried out subsequently to optimise the initial tool shape. In this step, the DA methodology is used to optimise the tool shape iteratively and the compensation factor α can be implemented to accelerate the optimisation procedures, as:

Fig. 6 Schematic showing iterative method to obtain springback compensation factor α . Black and grey curves respectively illustrate the method for determining α^2 within and out of the range of two initial points of α^0 and α^1

$$C^{i+1} = C^i - \alpha(S^i - O) \quad (26)$$

where C^i and C^{i+1} are tool shapes in current and next iterations, S^i is the formed shape with C^i , which can be obtained through CAF FE simulation. When the convergence criterion $\max(S^{i+1} - O) < e$ is achieved at the $(i+1)^{\text{th}}$ iteration, the finally optimised tool shape for CAF of the objective product is then obtained as C^{i+1} . The two-step ADA method for tool design for CAFed products with complex shapes is illustrated in Fig. 7.

4 Applications of accelerated springback compensation method for CAF of AA6082

Two representative CAF cases with AA6082-T6 are studied in this section, one for a singly curved product and the other for a varying curved product, to demonstrate the capability and effectiveness of the developed method for tool design in CAF process of different products.

4.1 Case A: singly curved product

A singly curved AA6082-T6 plate with a uniform radius of 4700 mm was selected as the objective product for CAF process at 160 °C for 3 h. Figure 8a shows detailed dimensions of the objective plate, with a width of 180 mm, length of 550 mm and thickness of 4 mm.

Fig. 7 Flow chat of ADA method for tool design in CAF process of products with varying curvature

Fig. 8 Illustration of objective CAF products: **a** singly curved product (case A) and **b** product with varying curvature (case B, the contour represents the value along z axis)

The optimised tool shape for this case can be obtained by the one-step method in Section 3.1. The curvature of the objective shape is $k_1 = 1/4700 = 0.00021 \text{ mm}^{-1}$. According to the springback compensation curve of curvature for CAF of AA6082 at 160°C for 3 h (grey dashed line in Fig. 5a), the curvature of compensated tool shape is $k_0 = 0.00143 \text{ mm}^{-1}$, which means that the compensated tool shape for this case is a singly curved plate with a radius of $R_0 = 1/0.00143 = 699.3 \text{ mm}$. CAF test with this optimised tool shape was carried out and the details and corresponding results will be introduced in Section 5.1.

4.2 Case B: varyingly curved product

A section of a high speed train front skin panel, which has varying curvatures, was selected as the objective product for CAF process with 4 mm thick AA6082-T6. The process parameter for this product is set as stress-relaxation at 160°C for 5 h. The shape of the product is shown in Fig. 8b with a width of 280 mm, length of 550 mm and varying depth.

As mentioned in Section 3.2, FE model is used to simulate the loading stage and whole CAF process to assist the determination of compensation factor α in ADA method. The details of corresponding FE model are introduced in Section 4.4.

The first step of the ADA method introduced in Section 3.2 was carried out to obtain the initial tool shape and compensation factor α . From FE simulation of loading AA6082-T6 plate to the objective shape, the maximum effective stress in the loaded plate was obtained as $\sigma'_{e-\max} = \sigma_a = 75.3 \text{ MPa}$. According to corresponding springback compensation curve (black solid line in Fig. 5c), the desired initial tool shape should have a maximum effective stress of $\sigma_{e-\max} = \sigma_b = 288.5 \text{ MPa}$ after loading. The compensation factor α was then calculated by the secant method introduced in Section 3.2 with the convergence limit of $e_o = 5 \text{ MPa}$, which was set to be smaller than 2.0% of the maximum effective stress value ($\sigma_{e-\max}$) to guarantee a high accuracy. After 2 iterations with the secant method in Eq. (24), α was obtained as 2.48 and the convergence has been achieved with a maximum effective stress of 284.3 MPa

in the plate loaded to the determined tool shape. Hence, the initial tool shape for this case was determined by Eq. (23), as:

$$C^0 = 2.48 \times O \quad (27)$$

FE simulation of CAF process with the determined initial tool shape is performed subsequently. The required maximum error for the shape accuracy of the product was set as $e = 0.5 \text{ mm}$. The simulation results and subsequent springback compensation procedures in the second step of ADA method will be given in Section 5.2.

4.3 CAF experiments

A multi-point flexible forming tool, comprised of sparse pins and adjustable to generate different tool shapes, was used for CAF manufacture of both singly curved and varyingly curved products in this study, as shown in Fig. 9. Forty-five forming pins were evenly distributed with a 9×5 matrix pattern with the same interval of 60 mm in x and y directions in both top and bottom plates. Spring steel splines ($540 \times 30 \times 3 \text{ mm}$) were attached to each array of forming pins along x direction, so as to maintain a smooth surface. A silicon rubber sheet ($600 \times 300 \times 12 \text{ mm}$) was placed between lower splines and test plate to reduce stress concentrations in the plate during loading.

After optimised tool shapes for both cases were determined, the depth of each forming pin was adjusted to generate corresponding tool surfaces [32]. The splines, rubber sheet and test plate were then assembled into the prepared flexible tool for subsequent CAF test, as shown in Fig. 9b for case B. The whole CAF test includes three steps: 1) loading the tool until the upper and lower parts of the tool are in full contact with the test plate, and fixing the whole tool setup; 2) heating the whole tool setup to 160°C in a furnace and then holding for 3 or 5 h and 3) cooling the tool to room temperature and releasing the plate. The shape of formed plates was measured by a coordinate measuring machine (LKG90C, Nikon Metrology UK) with an accuracy of 0.01 mm.

Fig. 9 Illustration of multi-point flexible forming tool **a** with prepared pins and **b** with plate, rubber sheet and splines for CAF test of case B

4.4 FE modelling technique

FE model simulating the whole CAF process was employed to assist springback compensation for CAF process with varyingly curved products. A similar FE model for CAF process with the same flexible forming tool was developed in a previous study through PAM-STAMP [33]. Figure 10 shows a quarter of the FE model. Forming pins were modelled by hemisphere surfaces with rigid shell elements and the global mesh size was set as 1 mm. The test plate, upper and lower splines were modelled by the four-node quadrilateral shell element with the Batoz Q4 gamma formulation and the rubber sheet was modelled by the deformable solid element, both elements were defined to have a global mesh size of 5 mm.

The lower forming pins were fixed by constraining all translational (T_x , T_y and T_z) and rotational (R_x , R_y and R_z) freedoms, while the upper forming pins had only a translational freedom along z direction, as shown in Fig. 10b. Both test plate and splines were symmetrically constrained along their own centre lines in both x and y directions, the detailed constraints are shown in Fig. 10c.

Surface-to-surface contact scheme in PAM-STAMP was used to characterise contact conditions between each part to

avoid possible penetrations. The friction coefficients were defined according to particular contacting pairs, 0.2 for metal-rubber and 0.25 for aluminium-steel contact pairs [34].

The creep-ageing constitutive model of Eqs. (14) to (21) and hardening rule of Eq. (22) proposed for AA6082-T6 were implemented into PAM-STAMP as a material subroutine [22], to simulate the stress-relaxation behaviour of the test plate during CAF. The splines are supposed to remain elastic during CAF tests and were defined as an elastic material with $E = 210$ GPa. In addition, the rubber sheet was defined as an incompressible Neo-Hookean material and was modelled as [35]:

$$W = C_{10}(J_1 - 3) \quad (28)$$

where W is the strain energy per unit volume, J_1 is the first deviatoric strain invariant and C_{10} is a material constant which was set as 1.45 MPa in this study [34]. Poisson's ratio of the rubber sheet was given as 0.499.

FE model for the whole CAF process includes four main stages: initiation of positions and properties of the tool setup, loading, stress-relaxation and unloading (springback). The CAF process was modelled as an isothermal case.

Fig. 10 A quarter of FE model for CAF application of case B: **a** isometric view, **b** xz plane view and **c** boundary conditions in test plate, rubber sheet and splines

Fig. 11 **a** Images of the formed plate after CAF process and **b** comparison of objective singly curved shape ($R_1 = 4700$ mm, solid line) and formed shape (symbols) from CAF test with optimised tool from one-step method ($R_0 = 699.3$ mm, dashed line)

5 Results and discussion

5.1 One-step springback compensation method for CAF of singly curved product

CAF test of AA6082-T6 plate with the optimised tool shape with a uniform radius of 699.3 mm has been carried out. Figure 11a shows the formed product after CAF process. The deflection values along x direction in the plate with $y = 0$ after loading and CAF from both numerical and experimental results are plotted in Fig. 11b. The formed shape from CAF test corresponds well with the objective shape, with a maximum difference of 0.51 mm. The high accuracy of formed product verified the effectiveness of the one-step method for tool design in CAF manufacture of singly curved products.

5.2 ADA method for CAF of varyingly curved product

FE simulation of CAF process with the initial tool shape determined for case B in Section 4.2 has been performed, the maximum shape error between the formed shape from FE and the objective shape is about 2.19 mm, which exceeds the limit $e = 0.5$ mm. Hence, the second step of ADA method, as introduced in Section 3.2, is required for subsequent tool shape optimisation.

Fig. 12 Convergence of the maximum shape error with springback compensation iteration number by conventional DA and ADA method (results from FE simulation)

In order to show the efficiency of ADA method proposed in this study, the same case has also been simulated using conventional DA method introduced in Fig. 1. Figure 12 shows the evolution of maximum shape error between formed shapes from FE modelling and the objective shape with iteration numbers from both methods. A decreasing trend with increasing iteration numbers is observed for both maximum shape error curves, indicating the effectiveness of the ADA and DA methods in springback compensation. As the results were obtained from FE models and the maximum error may occur at different nodes in the test plate at different iterations, a slight variation of the decreasing rate at different iteration number is observed. With ADA method, the maximum error was controlled within 0.5 mm after only 3 iterations and the value further decreased to 0.31 mm in the 4th iteration. While with conventional DA method, 11 iterations were needed to achieve a maximum shape error within 0.5 mm and the value was further decreased to 0.42 mm in the 12th iteration. The results show that ADA method has increased the convergence efficiency for tool design in CAF process of varyingly curved products by 3 times.

Fig. 13 Comparison of optimised tool shapes after 12 iterations with conventional DA method (solid lines) and 4 iterations with ADA method (dashed lines) for case B

Fig. 14 Image of the formed varyingly curved product (case B) with optimised tool shape after 4 iterations of ADA method

Figure 13 compares optimised tool shapes obtained from ADA method after 4th iteration and conventional DA method after 12th iteration by deflections along y axis with selected x values ($x = 0, 120$ and 240 mm). Both shapes show good agreement with each other and the maximum difference is about 0.75 mm, which is the reason for the different maximum shape errors in the CAFed plates with the two tool shapes shown in Fig. 12.

CAF test with the optimised tool shape obtained from fourth iteration of ADA method has been carried out and the images of the formed product after CAF process are shown in Fig. 14. The experimental results have been compared with the objective shape and corresponding FE results in Fig. 15. The experimental results of formed shape show a good agreement with the objective shape and FE predicted shape. Although slight discrepancies occur in some areas (e.g., Figs. 15c and d), which may result from

stress concentrations around forming pins of the flexible forming tool [33], the maximum difference between experimental results and the objective shape is 0.38 mm, corresponding well with the same data of 0.31 mm from FE simulation in Fig. 12. These results show that the proposed ADA method assisted by CAF FE models can significantly improve the tool design efficiency for CAF manufacture of complexly shape products.

6 Conclusions

An accelerated springback compensation method integrating springback mechanism of plate bending with creep-ageing behaviour of materials has been developed for the first time for tool design in CAF process. The effectiveness and high efficiency of the developed method have been verified through different CAF applications with a representative heat treatable aluminium alloy AA6082-T6. The following conclusions can be drawn:

1. A method to establish springback compensation curves reflecting curvatures, stress and strain relationships between plates loaded to objective shape and compensated tool shape has been proposed according to springback mechanism and stress-relaxation behaviour of CAF process. The application of the method for tool design for both singly and varyingly curved

Fig. 15 Comparison of deflections (z values) along y axis with $x = 0, 120, 240$ and -240 mm from the objective shape (solid lines) and formed shapes from CAF FE simulation (dashed lines) and experiment (symbols) with optimised tool shape by ADA method (4 iterations) for case B

products in CAF process has been demonstrated with AA6082-T6.

2. A one-step springback compensation method has been proposed for CAF of singly curved products. The method has been successfully applied to tool design for CAF of AA6082-T6 for a product with a uniform radius of 4700 mm. CAF test with the optimised tool shape achieved a high dimensional accuracy with the maximum shape error of 0.51 mm.
3. An accelerated displacement adjustment method based on springback compensation curves and FE simulations has been proposed for CAF of varyingly curved products. ADA method has significantly improved the convergence speed for CAF tool design. To achieve a maximum shape error within 0.5 mm for the complexly shaped product used in this study, convergence efficiency has been improved by 3 times with ADA method than with conventional DA method. The accuracy of the proposed method has been verified by corresponding CAF tests.
4. The new springback compensation method developed in this study can be used for high-efficient tool design for CAF of various products.

Acknowledgements The research was performed at the CRRC Sifang-Imperial Centre for Rail Transportation Manufacturing Technologies at Imperial College London. The authors would like to thank Mr. Suresh Viswanathan for his technical help in carrying out CAF tests.

Funding information This work was supported by CRRC Qingdao Sifang Co., Ltd.

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