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Formability behaviors of 2A12 thin-wall part based on DYNAFORM and stamping experiment

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ABSTRACT

A method integrating theoretical analysis, numerical simulation and experimental methods was adopted to solve the existing problems, including fillet less-plumping, cracks and wrinkling, in the forming process of a double curvature, thin-wall aluminum alloy part (DCTAP) of the aircraft skin. The mechanical properties of a 0.5 mm thick aluminum alloy sheet (2A12) were obtained through the uniaxial tensile test. The optimal blank holder force (BHF), blank shape (BS) and blank dimension (BD) were obtained by simulation using DYNAFORM. A stamping die was fabricated for experiment validation. The experimental results obtained by the coordinate grid strain analysis technology (CGSAT) agreed well with the simulation results, which demonstrated that the method presented here conduced to improving the formability of DCTAP.

1. Introduction

Thin-walled aluminum alloy shells have been increasingly applied with the development of aeronautics, aerospace and military industry [1]. However, the description of the mechanical properties and the deformation mechanisms and the forming laws of the thin-walled aluminum alloy shell are difficult to obtain by using traditional analytical and experimental methods. The finite element method (FEM) combined with analytical and experimental methods [2] is an effective way to study the deformation mechanisms and the forming laws of the thin-walled aluminum alloy shell [3,4]. The FEM formulation is not suitable for the numerical modeling of the material behaviors of aluminum alloys because the current material descriptions are good for the steel but not for aluminum alloys [5]. During the forming process of the aluminum alloy part, the material behaviors such as the anisotropic characteristics of the aluminum alloy have great influences on the strain distribution, the thinning rate of wall-thickness (TR), etc. in the forming process. At present, the plastic anisotropy was quantitatively described by the yield locus of the material.

The classical Von Mises yield criterion [6] was first proposed for the description of the anisotropy. Based on the Von Mises yield criterion, Hill (1948) proposed the widely used quadratic yield criterion for the description of the anisotropy of the sheet plane [7], yet the hydrostatic pressure is not considered in his yield criterion [8]. The three-component anisotropic yield function was proposed by Barlat and Lian (1989) and its yield surface is set in accordance with the measured yield surface based on the crystallographic theory. The six-component yield function presented by Barlat et al. [9,10] can be applied in 3D elasto-plastic finite element (FE) analysis. The yield functions proposed by Karafillis, Boyce and Cazacu et al. for anisotropic materials agree well with experimental results because the coefficient of normal anisotropy (γ) and the yield locus direction are considered in the functions [11]. Banabic et al. proposed a yield function for the study of the yield properties of St1405 and Al–Mg–Si alloy [12] and proved that the Banabic (1999) function is better than the Hill (1948) and Hill (1993) functions. A new eight-coefficient orthotropic anisotropic yield function was proposed by Banabic et al. in 2005 [13] and experimentally validated by the forming of the aluminum alloy sheet. Sun et al. demonstrated that the wrinkling and rupture predicted by the superquadric yield function are more accurate than those obtained by the quadric yield function since more parameters in the forming process are considered in the superquadric yield function [14]. The above studies mainly focus on theories and numerical computations of the metal sheet forming. However, the forming process of a double curvature, thin-wall aluminum alloy part (DCTAP) has never been profoundly studied.

In this paper, a method integrating theoretical analysis, numerical simulation and experimental methods is adopted to solve the existing problems including fillet less-plumping, cracks and wrinkling in the forming process of a DCTAP (0.5 mm thick; 2A12) of the aircraft skin. The blank holder force (BHF), blank shape (BS)

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and blank dimension (BD) were simulated using DYNAFORM and the optimal values for them were obtained. The mechanical properties of the aluminum alloy sheet were obtained by the uniaxial tensile experiment. The Baralt (1989) yield criterion, the J_2-flow law [15] and the mechanical properties of the material were used to improve the simulation results. Then, a stamping die set was designed and fabricated to conduct stamping experiments using CGSAT. The experimental results agreed well with the simulation results.

2. Basic theories

The equivalent stress in the Barlat 1989 criterion is defined by the following relation,

$$f = a|K_1 + K_2|^m + a|K_1 - K_2|^m + c|2K_2|^m = 2\bar{\sigma}^m \quad (1)$$

$$\text{with} \quad \left.\begin{aligned} K_1 &= \tfrac{\sigma_{11}+h\sigma_{22}}{2} \\ K_2 &= \sqrt{\left(\tfrac{\sigma_{11}-h\sigma_{22}}{2}\right) + p^2\sigma_{12}^2} \end{aligned}\right\} \quad (2)$$

where K_1 and K_2 are the principal values of the stress deviator, $\bar{\sigma}$ is the equivalent stress and σ_{ij} is the component of the effective stress tensor in the orthotropic rotated axes. a, c, h and p are the parameters of material anisotropy, and $a + c = 2$ and m is the exponents relevant to the crystal structure of the material. For aluminum alloy, $m = 8$, and for steel, $m = 6$ [16].

The specimen used for the uniaxial tensile test is cut at an angle φ, as shown in Fig. 1. In this case, the non-zero components of the stress tensor in the orthotropic axes are given by the following equations:

$$\left.\begin{aligned} \sigma_{11} &= \sigma_\varphi \cos^2 \varphi \\ \sigma_{22} &= \sigma_\varphi \sin^2 \varphi \\ \sigma_{12} &= \sigma_\varphi \sin \varphi \cos \varphi \end{aligned}\right\} \quad (3)$$

where $\phi \in (0,90°)$, and σ_φ is the yield stress obtained by the uniaxial tensile test.

When the volume is constant, Eq. (3) can be rewritten as,

$$\left.\begin{aligned} \sigma_\varphi d\varepsilon_{xx}^p &= \sigma_{11} d\varepsilon_{11}^p + \sigma_{22} d\varepsilon_{22}^p + 2\sigma_{12} d\varepsilon_{12}^p \\ \sigma_\varphi d\varepsilon_{yy}^p &= \sigma_{11} d\varepsilon_{11}^p + \sigma_{22} d\varepsilon_{22}^p - 2\sigma_{12} d\varepsilon_{12}^p \end{aligned}\right\} \quad (4)$$

Based on the Drucher postulate, the plastic strain increment $d\varepsilon_{ij}^p$ is written as,

$$d\varepsilon_{ij}^p = d\lambda \frac{\partial f}{\partial \sigma_{ij}} \quad (5)$$

The coefficients of plastic anisotropy within the range of the angles $\varphi \in (0,90°)$ are defined as,

$$\gamma_\varphi = \left| \frac{\bar{\sigma}}{\left(\frac{\partial f}{\partial \sigma_{11}} + \frac{\partial f}{\partial \sigma_{22}}\right)\sigma_\varphi} - 1 \right| \quad (6)$$

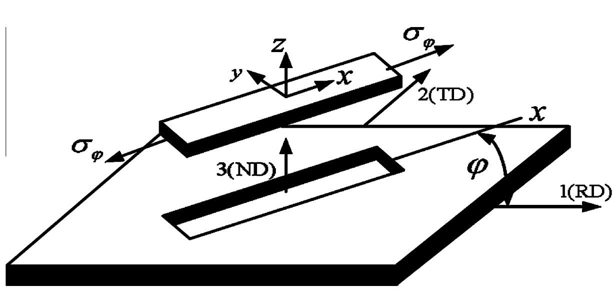

Fig. 1. Coordinate of specimen.

The coefficients of plastic anisotropy γ_0 and γ_{90} are substituted in Eq. (6), so Eq. (7) is obtained as below,

$$\left.\begin{aligned} a &= 2 - 2\sqrt{\tfrac{r_0}{1+r_0}\tfrac{r_{90}}{1+r_{90}}} \\ h &= \sqrt{\tfrac{r_0}{1+r_0}\tfrac{1+r_{90}}{r_{90}}} \\ c &= 2\sqrt{\tfrac{r_0}{1+r_0}\tfrac{r_{90}}{1+r_{90}}} \end{aligned}\right\} \quad (7)$$

Based on the Newton–Raphson iterative method, the parameter p is calculated by,

$$g(p) = \frac{\bar{\sigma}}{\left(\frac{\partial f}{\partial \sigma_{11}} + \frac{\partial f}{\partial \sigma_{22}}\right)} - 1 - \gamma_{45} \quad (8)$$

The J_2-flow constitutive equation is defined as,

$$\tilde{\tau}_{ij} = \frac{E}{1+\upsilon} \cdot \left[\delta_{ik}\delta_{jl} + \frac{\upsilon}{1-2\upsilon}\delta_{ij}\delta_{kl} - \frac{3\alpha\left(\frac{E}{1+\upsilon}\right)\sigma'_{ij}\sigma'_{kl}}{2\bar{\sigma}\left(\frac{2}{3}H' + \frac{E}{1+\upsilon}\right)} \right] \dot{\varepsilon}_{kl} \quad (9)$$

where $\tilde{\tau}_{ij}$ is Jaumann rate of Cauchy stress and σ_{ij} is Cauchy stress and σ'_{ij} is Deviatoric part of σ_{ij}; H' is strain-hardening rate and E is elastic modulus and υ is Poisson ratio; α is value of unity for plastic state and zero for elastic state or unloading and $\dot{\varepsilon}_{ij}$ is strain rate and $d\lambda$ is plastic flow factor. The J_2-flow law is simplified since all material constants are determined by the uniaxial tension test [15].

The relationship of the true tensile stress σ and the true tensile strain ε can be written as,

$$\left.\begin{aligned} \varepsilon &= \ln \tfrac{l}{l_0} \\ \sigma &= \tfrac{F}{S} = \tfrac{F}{S_0}\tfrac{l}{l_0} \end{aligned}\right\} \quad (10)$$

where F is the tensile force; S_0, l_0 and S, l are the cross-sectional area and the gauge length of the extensometer at the initial and current time points, respectively. The true tensile strain at the end of the uniaxial tension was obtained by calculating the current cross-section area by $S = S_0 l_0 / l$ and neglecting the elastic deformation of the specimen.

The relation between $\bar{\sigma}$ and the equivalent plastic strain $\bar{\varepsilon}$ is used to describe the hardening behavior of the material, as shown in the following equation

$$\ln \bar{\sigma} = \ln K + n \ln \bar{\varepsilon} \quad (11)$$

where n is the strain-hardening exponent and K the material constant. The inclined rate n is obtained using Eq. (11) and the least square method [17]. A total of 20 experiment points obtained in the uniformity deformation stage are tested in this paper to better reflect the degree of material work hardening.

The other parameters are calculated using Eq. (12),

$$\bar{X} = (X_0 + 2X_{45} + X_{90})/4. \quad (12)$$

3. Numerical analysis

3.1. Material properties

The mechanical properties of 2A12 [18] were obtained using the uniaxial tensile experiment and shown in Table 1.

3.2. Numerical analysis

FE simulations and related experiments are performed to show the formability behaviors and anisotropic effect of the 2A12 sheet in the forming process of DCTAP (Fig. 2). The material model is established based on the Barlat (1989) yield function and the mechanical properties of the material are imported into the material library of DYNAFORM. Values of K, n and γ are given in Table 1. The