



# 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 conducted to improving the formability of DCTAP.

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## 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 ( $\gamma$ ) 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 Barlat (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,

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

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

where  $K_1$  and  $K_2$  are the principal values of the stress deviator,  $\bar{\sigma}$  is the equivalent stress and  $\sigma_{ij}$  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  $\phi$ , 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:

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

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

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

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

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

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

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

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

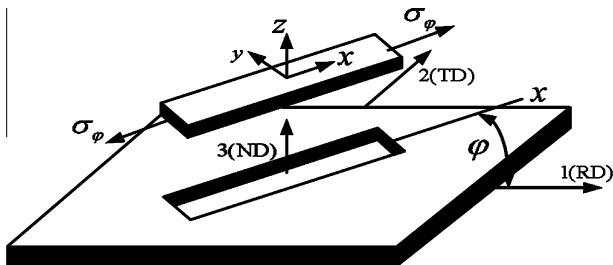


Fig. 1. Coordinate of specimen.

The coefficients of plastic anisotropy  $\gamma_0$  and  $\gamma_{90}$  are substituted in Eq. (6), so Eq. (7) is obtained as below,

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

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,

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

where  $\dot{\tau}_{ij}$  is Jaumann rate of Cauchy stress and  $\sigma_{ij}$  is Cauchy stress and  $\sigma'_{ij}$  is Deviatoric part of  $\sigma_{ij}$ ;  $H'$  is strain-hardening rate and  $E$  is elastic modulus and  $\nu$  is Poisson ratio;  $\alpha$  is value of unity for plastic state and zero for elastic state or unloading and  $\dot{\epsilon}_{ij}$  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  $\sigma$  and the true tensile strain  $\epsilon$  can be written as,

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

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-sectional 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  $\bar{\epsilon}$  is used to describe the hardening behavior of the material, as shown in the following equation

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

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  $\gamma$  are given in Table 1. The

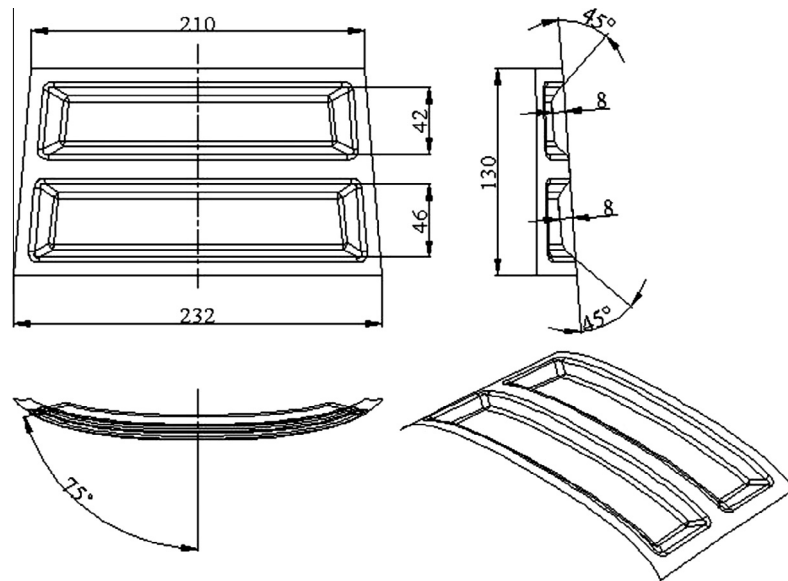


Fig. 2. Schematic diagram of 2A12 DCTAP.

Table 1

Mechanical properties of the aluminum alloy 2A12.

| Direction       | $E$ (GPa) | $K$ (MPa) | $n$   | $\gamma$ |
|-----------------|-----------|-----------|-------|----------|
| Transverse (90) | 72.342    | 635.443   | 0.147 | 0.693    |
| 45°             | 72.142    | 585.751   | 0.111 | 0.832    |
| Rolling (0°)    | 70.863    | 602.801   | 0.126 | 0.337    |
| Mean value      | 71.872    | 602.437   | 0.124 | 0.674    |

velocities of punch and binder are set as 5000 mm/s and 2000 mm/s, respectively. The other parameters including the density, hardening rule, friction coefficient and Poisson ratio are set to  $2.7 \times 10^3 \text{ Kg/m}^3$ , 2, 0.12 and 0.3, respectively. The friction type is set as the contact-one-way-surface-to-surface mode and adaptive meshing method is adopted to mesh the geometry model. The friction conditions are set according to those used in the experiments.

The simulation results are shown in Figs. 4, 7 and 10. Regional districts in red, yellow, orange, green, gray, blue and pink colors denote rupture, risk of rupture, thickness reduction, safe forming, insufficient forming, impending wrinkling and wrinkling, respectively.

### 3.2.1. Simulation with variable BHF

Fig. 3 shows the blank shape (BS), which is a trapezoid obtained by unfolding the CAD model of the die in the DYNIFORM. The simulations of the forming process were performed with all parameters unchanged except BHF. According to the experimenters' experience, BHF for the simulations were set to 0, 22.5, 42.5 and 83 KN, respectively.

The simulation results with the varied BHF values are shown in Fig. 4. As is shown in Fig. 4(1), when BHF is 0 KN, the 2A12 specimen is severely wrinkled, with the wrinkles mainly distributed at all edges of the two grooves, but no cracks occur. Moreover, the impending wrinkling is commonly observed at all edges of the two grooves and the inner district of the longer groove. As is shown in Fig. 4(2), the wrinkling is still severe when BHF increases to 22.5 KN, but is less severe than that in Fig. 4(1). When BHF increases to 42.5 KN, the forming behavior improves obviously (Fig. 4(3)). The wrinkles are distributed in the fillets of the two grooves and the middle sections of the top and bottom boundaries of the two grooves, and then the specimen shows less likelihood of rupture. Furthermore, the impending wrinkling in Fig. 4(3), similar

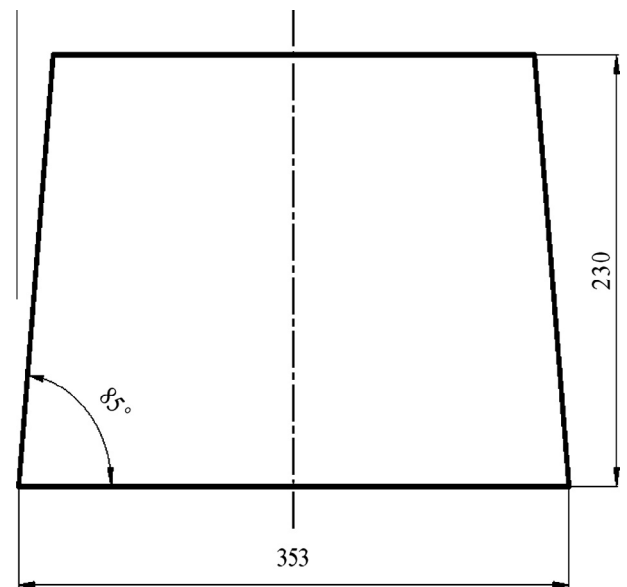


Fig. 3. Unfolding blank shape in DYNIFORM.

to that in Fig. 4(2), is mainly observed in the four outer fillets, part of the inner area of the two grooves and the specimen border. As is shown in Fig. 4(4), when BHF increases to 83 KN, the forming behavior remains almost the same as that in Fig. 4(3), but the inner districts of the two grooves show high crack risk.

Fig. 5 shows the relationships between BHF, TR and PS in the forming process of DCTAP. Of the four PSs, the plastic strain (PS) is the smallest when BHF is 42.5 KN. The TR increases at a decreasing rate when BHF increases from 42.5 to 83.5 KN. With Figs. 4 and 5 considered together, the optimal BHF value for the simulation is determined as 42.5 KN.

### 3.2.2. Simulation with variable blank dimension

When the optimal BHF value (42.5 KN) and BS (trapezoid) remain constant, the blank dimension (BD) of S1 (363 mm  $\times$  240 mm), S2 (353 mm  $\times$  230 mm), S3 (343 mm  $\times$  220 mm) and S4 (333 mm  $\times$

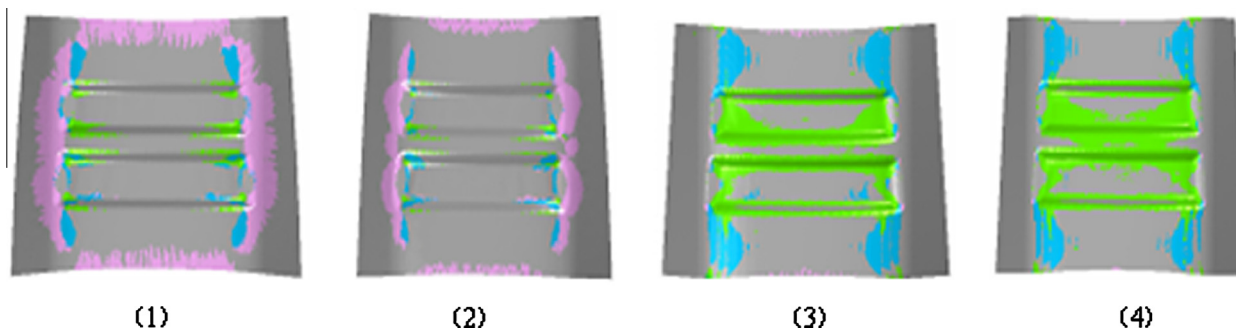


Fig. 4. Simulation with variable BHF: (1) BHF 0 and (2) BHF 22.5 and (3) BHF 42.5 and (4) BHF 83.5 KN.

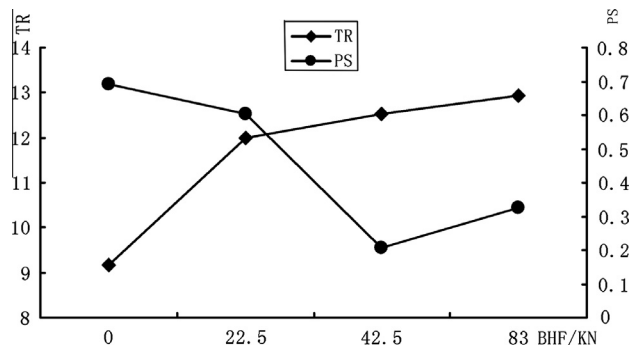


Fig. 5. Relationships between blank holder force (BHF), the thinning rate of wall thickness (TR) and plastic strain (PS).

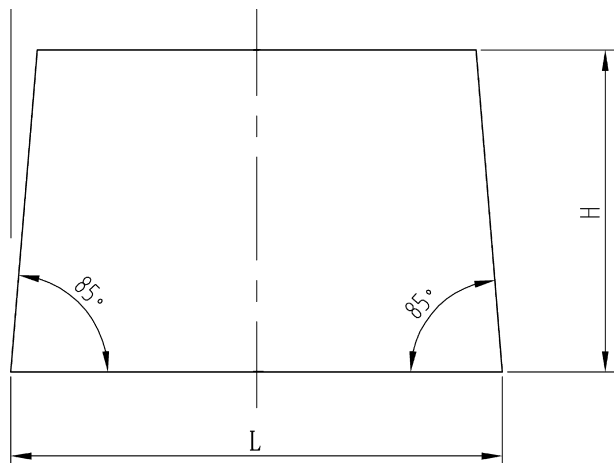


Fig. 6. Schematic diagram of blank dimension (BD).

210 mm) (Fig. 6 and Table 2) are imported into DYNAFORM for simulations of the forming process of DCTAP, respectively.

The results of the simulations with the four BDs are shown in Fig. 7. It can be seen that the two grooves at S1 show higher crack risk than those at S2. The wrinkling areas at S3 and S2 mainly centered in the inner district of the longer groove, but the wrinkling at S3 is more severe than that at S2. Of the four BD conditions, the wrinkling and impending wrinkling are the most severe at S4.

Fig. 8 depicts the relationships between BD, TR and PS. Of the four BD conditions, the TR is the largest at S1 and the PS is the largest at S4. Furthermore, the PSs and TRs at S2 and S3 show negligible differences. Therefore, S2 (353 mm × 230 mm) is determined as the optimal BD for simulations of the forming process of DCTAP.

### 3.2.3. Simulation with variable BS

When the optimal BHF value (42.5 KN) and the BD (353 mm × 230 mm) remain constant, specimens with four differ-

Table 2  
Blank dimensions.

| Level | L (mm) | H (mm) |
|-------|--------|--------|
| S1    | 363    | 240    |
| S2    | 353    | 230    |
| S3    | 343    | 220    |
| S4    | 333    | 210    |

ent shapes (Fig. 9) are used for simulations to study the influence of BS on the quality of the final formed part and determine the optimal BS for the simulation of the forming process of DCTAP.

The results of simulations with varied BS are shown in Fig. 10. It can be seen that the RC shape shows the most notable safety area for the DCTAP formation. Of the four blank shapes, the RC shape shows the least severe impending wrinkling, mainly observed in the area from the four outer fillets to the specimen border. For the R shape, the wrinkling does not occur obviously, but the inner districts of the two grooves show high risk of cracks. The T shape shows a smaller safety area for the DCTAP formation than the R and RC shapes. Of the four blank shapes, the E shape has the largest wrinkling area and the most severe impending wrinkling.

Fig. 11 shows the relationships between BS, TR, and PS. Of the four blank shapes, the TR for the R shape is the largest, and the PS for the E shape is the smallest. Therefore, with Figs. 10 and 11 considered together, the RC shape is selected as the optimal BS for the simulation of the forming process of DCTAP.

## 4. Experiments and discussion

The stamping die (Fig. 12) was designed and fabricated based on the simulation results. The 45# steel (Chinese Standard) is chosen as the tool material, and a 0.5 mm thick aluminum alloy sheet (2A12) is chosen as the blank to conduct the following stamping experiments.

### 4.1. Stamping experiment with variable BHF

The shape and size of the blank used in the stamping experiment are shown in Fig. 3. The BHF are set to 0, 22.5, 42.5 and 83 KN, respectively. The experimental results are shown in Fig. 13.

It can be seen from Fig. 13(1) that the wrinkling is obvious but the rupture does not occur at 0 KN. The ultimate formed shape at 42.49 KN is superior to those at other BHF, thus 42.49 KN is the optimal BHF value for the forming process of DCTAP.

### 4.2. Stamping experiment with variable BD

When the optimal BHF value (42.49 KN) and BS (trapezoid) remain constant, BDs of S1 (363 mm × 240 mm), S2 (353 mm × 230 mm), S3 (343 mm × 220 mm) and S4 (333 mm × 210 mm)

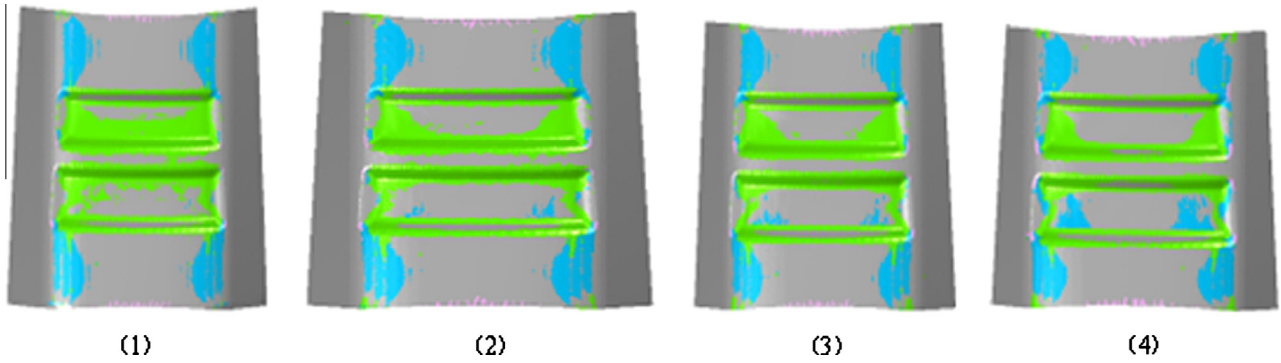


**Fig. 7.** Simulations with variable blank dimension (BD): (1) S1 (363 mm × 240 mm), (2) S2 (353 mm × 230 mm), (3) S3 (343 mm × 220 mm), and (4) S4 (333 mm × 210 mm).

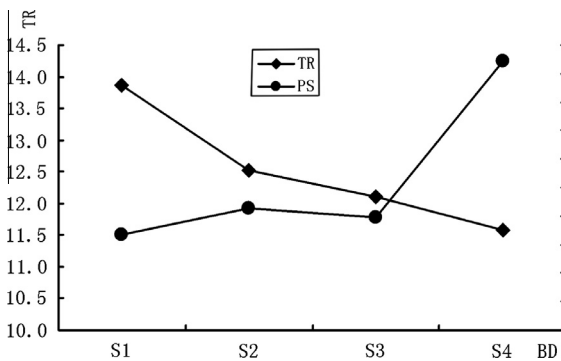


**Fig. 8.** Relationships between blank dimension (BD), the thinning rate of wall-thickness (TR) and plastic strain (PS).

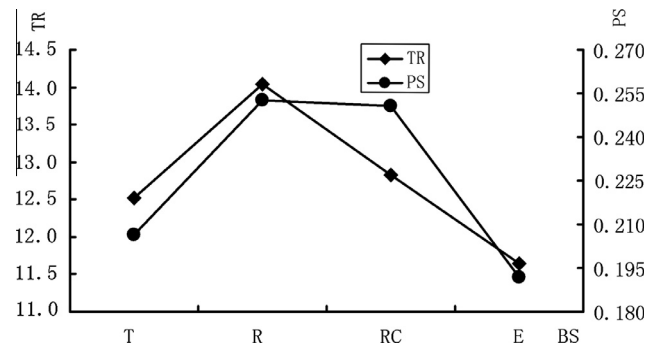


**Fig. 11.** Relationships between blank shape (BS), the thinning rate of wall-thickness (TR) and plastic strain (PS).

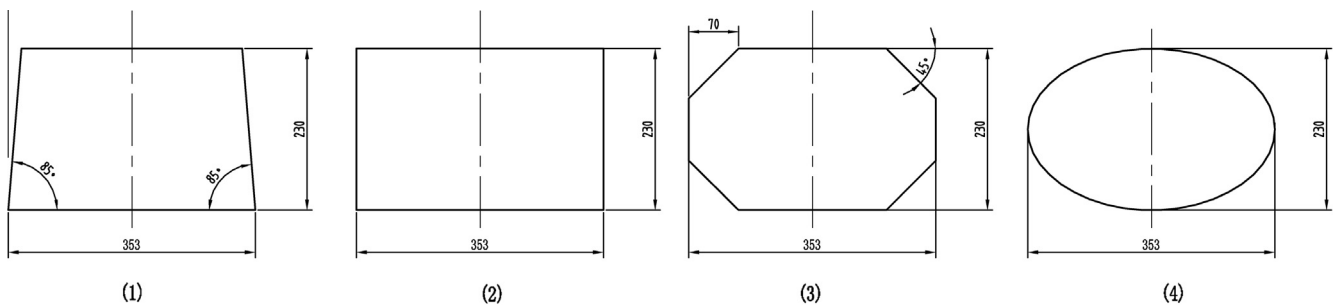


**Fig. 9.** Blank shapes: (1) trapezoid (T) and (2) rectangle (R) and (3) rectangle with chamfers (RC) and (4) Ellipse (E).

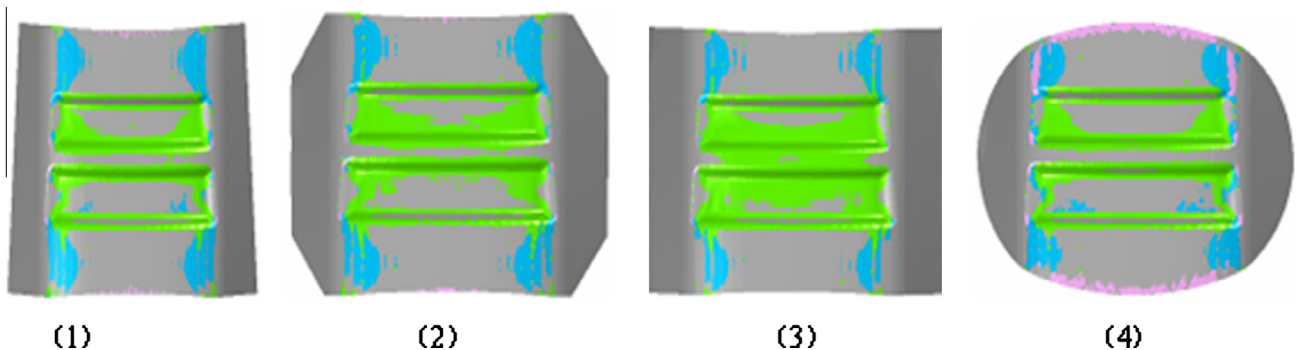


**Fig. 10.** Simulations with variable blank shape (BS): (1) trapezoid (T) and (2) rectangle (R) and (3) rectangle with chamfers (RC) and (4) Ellipse (E).



Fig. 12. Schematic diagram of stamping die assembly.

are adopted to conduct the experiments. The experimental results are shown in Fig. 14.

Fig. 14(2) shows that formability at S2 is the best among the four BDs; therefore, S2 (353 mm × 230 mm) is the optimal BD for the forming process of DCTAP.

#### 4.3. Stamping experiment with variable BS

When the optimal BHF (42.49 kN) and the optimal BD (353 mm × 230 mm) remain constant, the four blank shapes shown in Fig. 9 are used to conduct the stamping experiment and the results are shown in Fig. 15.

For the T shape (Fig. 15(1)) and R shape (Fig. 15(2)), the formability at the two grooves meets the basic quality requirements for the DCTAP; however, the wrinkling occurs at the border of the blank, which has negative effects on the quality of the final formed part. According to Fig. 15(3), the RC shape shows the optimal formability among the four blank shapes. The formability of the RC shape is improved probably due to the chamfers of the four corners of the blank. The formability of the E shape is the poorest (Fig. 15(4)), which might be caused by the insufficient metal flow at the blank border. Thus, the RC shape is the optimal BS for the forming process.

#### 4.4. Coordinate grid strain analysis (CGSA)

The results of the stamping experiments show good agreement with the simulation results. In this section, the accuracy of the optimal values for BHF, BS and BD obtained by simulations is further validated by CGSA. When BHF (42.49 kN) and BD (353 mm × 230 mm) remain constant, the four blank shapes shown in Fig. 9 are used to conduct CGSA, respectively. Grids are highlighted on the surface of the RC-shaped specimen, as shown in Fig. 16. In Fig. 16, the numbers 1–84 represent the serial numbers of individual grids and the English alphabets A to G represent the different sections of the specimen.

Grids of the specimens with the four blank shapes are measured by the JX-6 reading microscope with amplification 20 times and measurement precision 0.01 mm. Eighty-four grids on each specimen are tested to capture the strain data [19]. In order to facilitate the analysis, all grids are divided into eight groups. Every ten grids are taken as one group and the 8th group has fourteen grids. The eight groups are named  $GA_i$  ( $i = 1, 2, \dots, 8$ ). The strains for each group are measured and the average strain value is calculated.

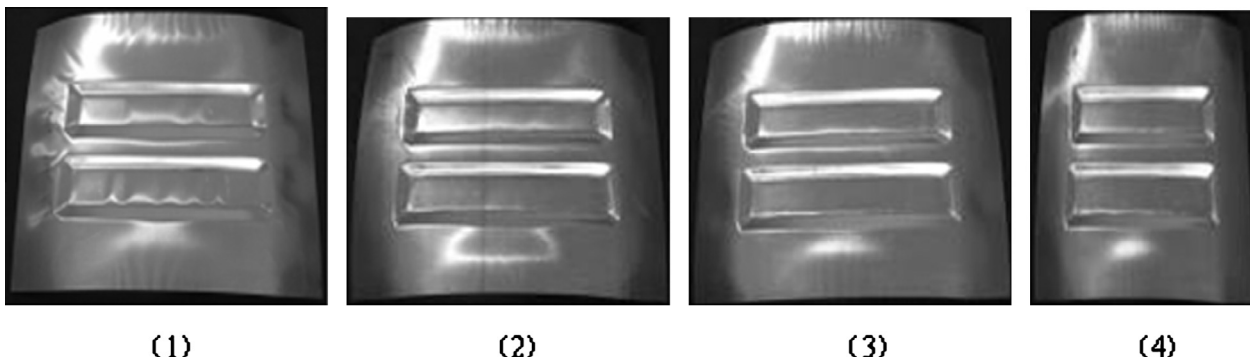


Fig. 13. Ultimate formed shapes with variable blank holder force (BHF): (1) 0 kN, (2) 22.37 kN, (3) 42.49 kN and (4) 83.28 kN.

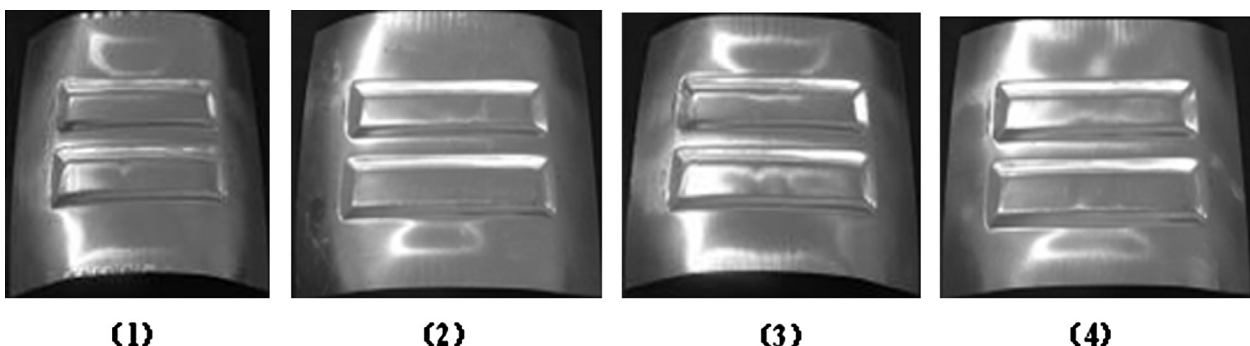


Fig. 14. Ultimate formed shapes with variable blank dimension (BD): ((1) S1 (363 mm × 240 mm), (2) S2 (353 mm × 230 mm), (3) S3 (343 mm × 220 mm), and (4) S4 (333 mm × 210 mm).

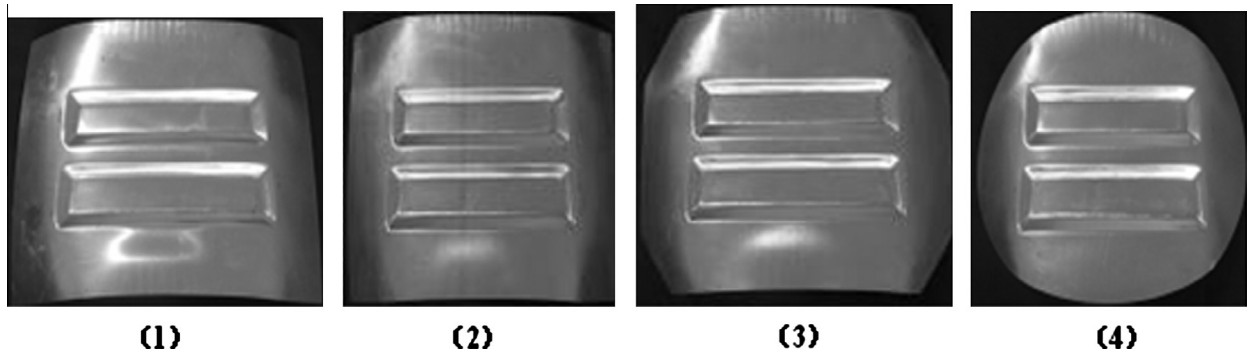


**Fig. 15.** Ultimate formed shapes with variable blank shape (BS): (1) trapezoid (T) and (2) rectangle (R) and (3) rectangle with chamfers (RC) and (4) Ellipse (E).

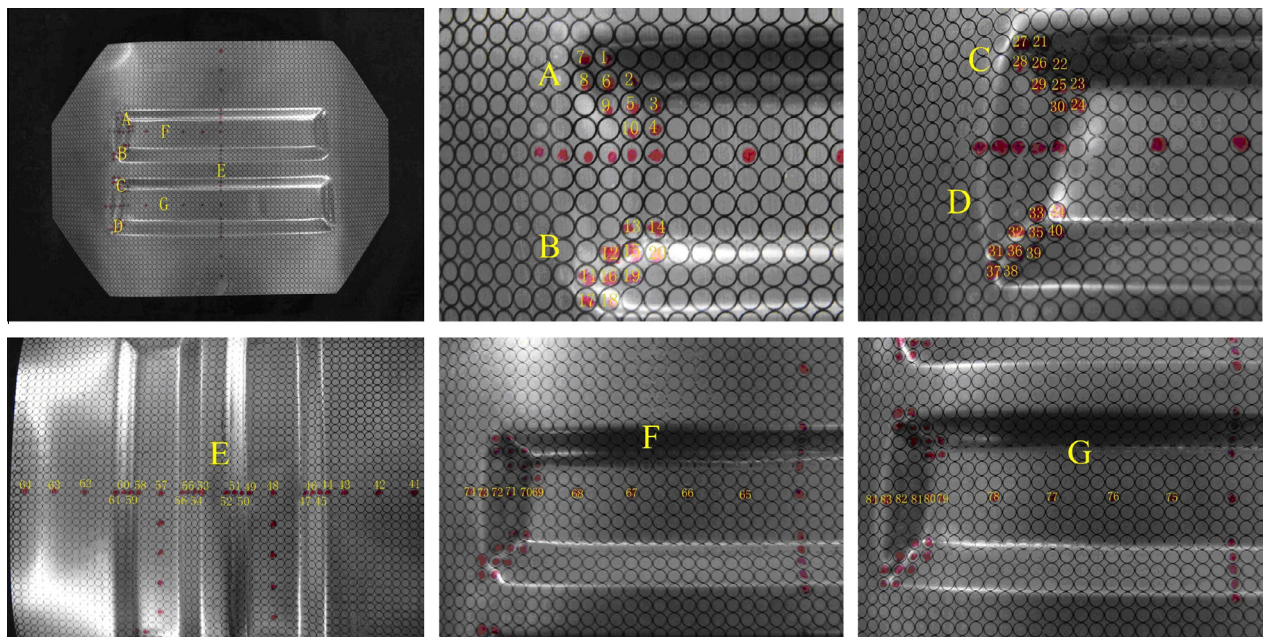


**Fig. 16.** Grids on rectangular specimen with chamfers.

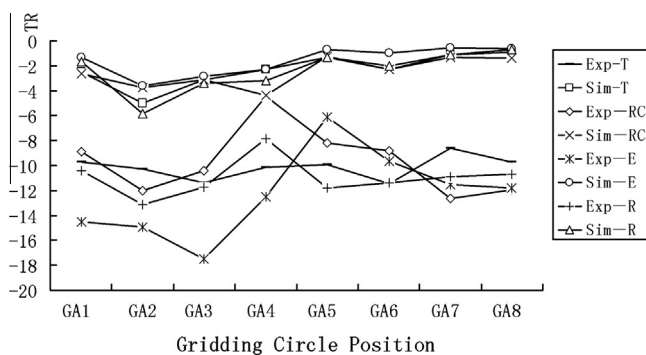


**Fig. 17.** Relationship between TR and average strain for each  $GA_i$ . Exp-T, Exp-R, Exp-RC and Exp-E respectively denote the four blank shapes used in the stamping experiments: trapezoid (T), rectangle (R), rectangle with chamfers (RC) and ellipse (E). Sim-T, Sim-R, Sim-RC and Sim-E respectively denote the four blank shapes (T, R, RC and E) used in numerical simulations.

The relationship between the TR value and the average strain value are obtained and depicted in Fig. 17.

As can be seen in Fig. 17, there are slight discrepancy in the strain distribution between the simulation and experimental

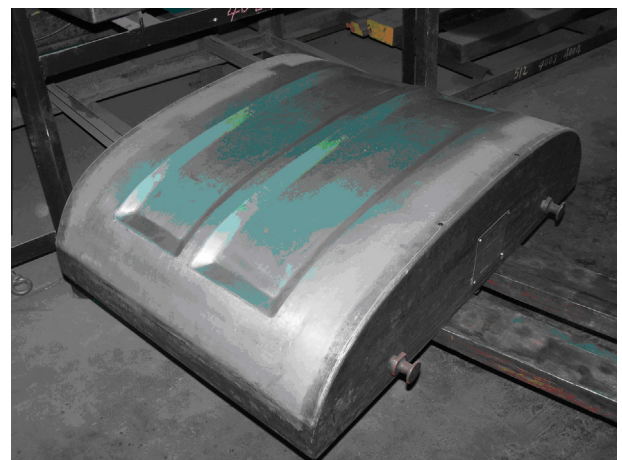


**Fig. 18.** The die used in the manufacture factory.

results, but this discrepancy is negligible. The problems of fillet less-plumping, cracks and wrinkling in the forming process of 2A12 DCTAP of the aircraft skin are well solved based on the Barlat



Fig. 19. The aircraft skin part manufactured in the factory.

(1989) yield criterion and the  $J_2$ -flow law. For each grid group, the average strain value obtained in the experiment is slightly smaller than those of the simulation probably because the actual working conditions in the experiments are not entirely the same as those of the simulations.

## 5. Engineering application

The DCTAP of the aircraft skin is manufactured in a factory based on the optimal BHF (42.49 KN), the optimal BD (353 mm × 230 mm) and the optimal BS (the RC shape) obtained in the simulations and stamping experiments. The stamping die (Fig. 18) was fabricated by using the 45# steel. A 0.5 mm thick aluminum alloy sheet (2A12) is used to form the DCTAP. Fig. 19 shows that the DCTAP manufactured in the factory satisfies the engineering requirements for the aircraft skin part.

## 6. Conclusions

- (1) Based on the DYNAFORM simulation and the related stamping experiments, the optimal BHF, BD and BS are 42.49 KN, (353 mm × 230 mm) and the RC shape.
- (2) The experimental results measured with CGSAT agree well with the simulation results, which demonstrates that the Barlat (1989) yield criterion and the  $J_2$ -flow law can well solve the existing problems such as fillet less-plumping, cracks and wrinkling in the forming process of the 2A12 DCTAP of the aircraft skin.

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