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Research on springback compensation for multi-point forming of corrosion-resistant aluminum alloy hyperbolic component

Han Shao[1], Yanlong Wang[3], Haixia Wan[2], Hongbo Wang[2], Zhongfeng Zhang[1], Wenzhi Fu[1]

[1]Jilin University, School of Material Science and Engineering, Changchun, China.

[2]CSSC Huangpu Wenchong Shipbuilding Company Limited, Guangzhou, China.

[3]First JS Representative Office of HJ in Guangzhou area, Guangzhou, China.

e-mail: 1147750832@qq.com, 390462984@qq.com, 568534267@qq.com, 272060977@qq.com, 1944962696@qq.com, fwz@jlu.edu.cn

ABSTRACT

Springback is the reverse elastic deformation produced by the unloading process, which is a common phenomenon in the sheet metal stamping and forming process and affects the final forming accuracy of the part. Aiming at the problem of springback error in the multi-point forming process of hyperbolic component for ships, the springback phenomenon of hyperbolic component was studied by combining theoretical analysis, numerical simulation and forming test. The mechanical property parameters and stress-strain curves were obtained by tensile tests using a new corrosion-resistant aluminum alloy as the sheet material. The springback compensation method is introduced, the springback compensation formula based on surface curvature is derived, and the compensated mold surface is further corrected and fitted using the cubic B-sample method. The multi-point punch tooling was generated and modeled by the multi-point 3D modeling software MPFCAD and finite element software to simulate the multi-point forming and unloading springback process of the hyperbolic member. Multi-point forming tests were conducted on a multi-point forming press for corrosion-resistant aluminum alloy hyperbolic component, and the formed parts were checked for accuracy and error analysis by 3D scanning and GOM Inspect software. The results show that the springback compensation method used in this paper can effectively reduce the springback error in the multi-point forming process of corrosion-resistant aluminum alloy hyperbolic component, and the effect is very good.

Keywords: Material Processing Technology; Aluminum alloy; Multi-point forming; Numerical simulation; Springback compensation.

1. INTRODUCTION

In recent years, with the rapid development of ship manufacturing industry, aluminum alloy has gradually become an important material for ship parts [1, 2], and aluminum alloy with excellent corrosion resistance will further improve the overall quality and service life of ships. As an efficient and flexible forming technology [3], multi-point forming disaggregates the traditional monolithic die into a series of tightly arranged, height-adjustable multi-point punch groups [4] as a way to accommodate parts of various shapes and sizes, and is particularly suitable for forming complex hyperbolic component.

The springback characteristics of the new corrosion-resistant aluminum alloy used in this paper seriously affect the forming accuracy of the hyperbolic component for ships, so it is important to study an effective springback compensation method for multi-point forming of corrosion-resistant aluminum alloy sheets.

Springback compensation is not only a technical difficulty in the traditional integral forming process, but also a common problem in the multi-point forming process, which has a great impact on the dimensional accuracy and forming quality of the parts. The springback compensation method using the springback law is an effective method to reduce the springback error, for which a large number of studies have been conducted by related scholars at home and abroad using theoretical analysis, numerical simulation and experimental testing [5], and there are many factors affecting the springback [6], and the construction models and analysis methods are different, and some research results have been achieved. XING *et al.* [7] have suppressed forming depression formation by changing the MPD arrangement of punch units. JIA *et al.* [8] have proposed a new individually controlled force-displacement multi-point forming method. LI and HU [9] have applied ultrasonic

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vibration-assisted forming in the stamping process. LIU *et al*. [10] have proposed a springback compensation algorithm that takes into account the anisotropy of hyperboloid plates. ALAVIZADEH and KARAMI [11] have designed and fabricated a new reconfigurable hydroforming die. BORMOTIN and WIN [12] have used a reconfigurable rod punch to model the sheet forming process in creep mode. LI *et al*. [13] have conducted a theoretical analysis of the wide plate bending and forming and elongation process. ZHANG *et al*. [14] have proposed a method to modify the forming surface of the basic body group to compensate for springback to obtain accurately shaped parts. Therefore, this paper investigates the springback phenomenon and its compensation in the multi-point forming process of the new corrosion-resistant aluminum alloy marine hyperbolic member, and verifies it by multi-point forming test.

2. HYPERBOLIC COMPONENT AND MATERIAL PROPERTIES

2.1. Hyperbolic component

Numerical simulation of the multi-point forming process is carried out for the forming of a hyperbolic member, the surface shape of which is shown in Figure 1.

The curvature of the hyperbolic member in the length direction AB (or CD) is about 700 mm, in the width direction BC (or AD) is about 500 mm, and in the thickness direction 3 mm. it can be seen from Figure 1 that the curvature of the hyperbolic member in the length direction AB (or CD) is almost constant; in the width direction BC (or AD), the curvature decreases gradually from end point B (or A) to end point C (or D). It can be seen that the hyperbolic member is a quasi-unidirectional complex curvature surface member of variable curvature.

2.2. Material properties

According to the material tensile test standard, combined with the test machine clamp size and parts material size, design the material tensile test specimen drawing as shown in Figure 2. The design length of the corrosion-resistant aluminum alloy tensile specimen is L = 54 mm, the design width of the specimen is D = 18 mm, the length of both ends of the clamping part is D_1 = 12.6 mm, the design initial length of the tensile zone (original pitch) l_0 = 18 mm, the initial width d_0 = 7.2 mm, the initial thickness (taken from the thickness of the part plate) h_0 = 4 mm.

In order to have a more comprehensive understanding and grasp of the mechanical property parameters of the corrosion-resistant aluminum alloy, the specimens were mainly processed in three directions (0°, 45° and 90° from the rolling direction). Three specimens (No. 1, 2, 3) processed at 0° with the rolling direction of the

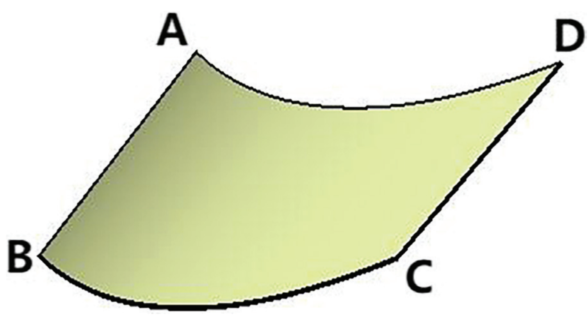

Figure 1: Hyperbolic component.

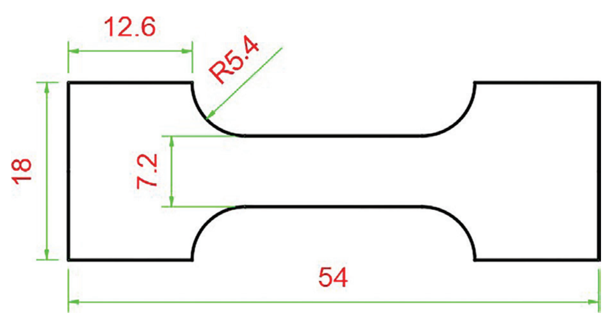

Figure 2: Dimensional parameters of specimens.

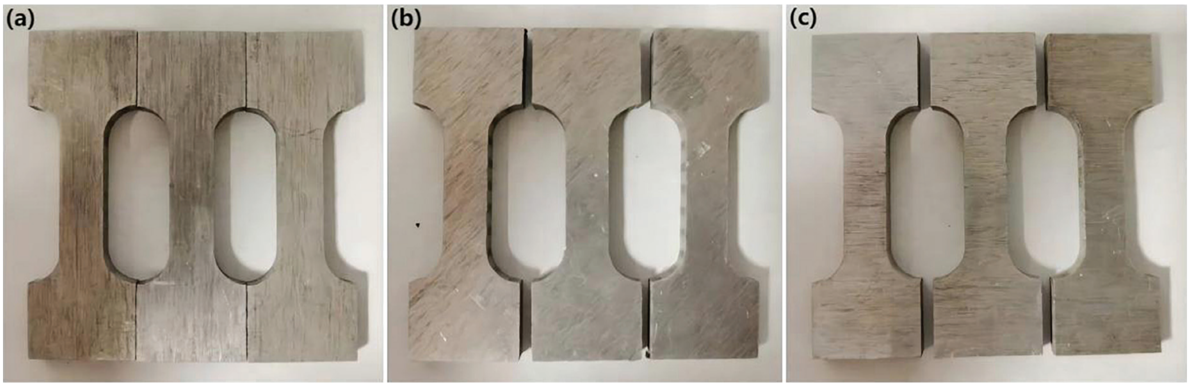

Figure 3: Processed specimens.

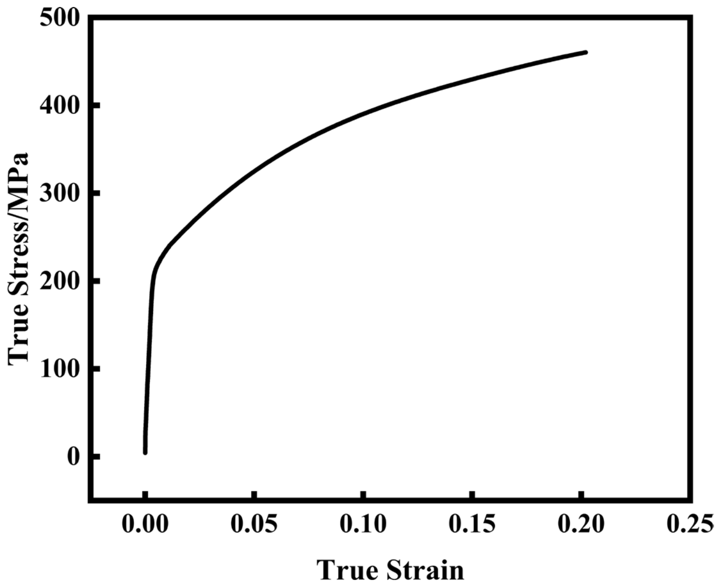

Figure 4: Stress-strain curve of corrosion-resistant aluminum alloys used in this paper.

plate are shown in Figure 3a, three specimens (No. 4, 5, 6) processed at 45° are shown in Figure 3b, and three specimens (No. 7, 8, 9) processed at 90° are shown in Figure 3c, for a total of three groups of nine.

Through the tensile test of corrosion-resistant aluminum alloy specimen, the data of tensile force and tensile amount of aluminum alloy specimen were measured, and then after data processing, the real stress-strain curve was obtained as shown in Figure 4. From the experimental results, it is known that the yield strength of the corrosion-resistant aluminum alloy material is 216.38 MPa, the modulus of elasticity is 68365.86 MPa, and the Poisson's ratio is 0.3.

3. SPRINGBACK COMPENSATION METHOD AND CALCULATION

3.1. Springback compensation method

The springback compensation method (shown in Figure 5) compensates for springback by pre-correction of the mold profile. By applying a compensation amount to the mold that is opposite to the direction of springback, the unloaded surface is the desired target shape. The curvature before springback is calculated from the target shape curvature (the curvature to compensate for springback), and the required surface is obtained from the curvature before springback, also called the springback compensation surface. In multi-point forming, it is necessary to adjust the height of the basic body punch that forms the multi-point die surface, and the multi-point die shaping surface is the surface that has already compensated the amount of springback. The shaping and unloading process is carried out on the sheet according to the shaped multi-point die face to obtain the required target shape (qualified part).

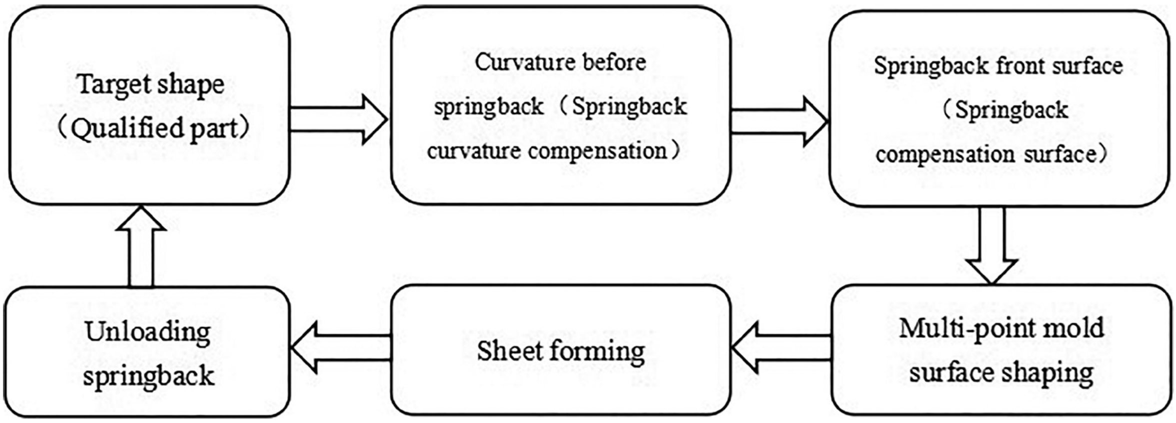

Figure 5: Springback compensation method.

3.2. Springback compensation calculation

According to the stress-strain curves obtained in 2.2 for the corrosion-resistant aluminum alloy, they are consistent with the power exponential material strengthening model. Therefore, in order to accurately describe the stress-strain relationship of the corrosion-resistant aluminum alloy, the following equation is used [15].

$$\sigma = \begin{cases} E\varepsilon & \varepsilon \le \sigma_s/E \\ \sigma_s + K\left(\varepsilon - \dfrac{\sigma_s}{E}\right)^n & \varepsilon \ge \sigma_s/E \end{cases} \quad (1)$$

σ is the stress, ε is the strain, E is the modulus of elasticity, σ_s is the yield strength, K is the strengthening factor, n is the work hardening index.

According to the generalized Hooke's law and Mises' yield criterion:

$$\begin{cases} \sigma_y = 0, \varepsilon_z = 0 \\ \sigma_s' = \sigma_x = \dfrac{\sigma_s}{\sqrt{1-\mu+\mu^2}} \end{cases} \quad (2)$$

σ_x, σ_y denotes the stress in x and y directions respectively, ε_z is the strain in z direction, μ is the Poisson's ratio.

Bending moment formula:

$$M = 2\int_0^{z_s} E\varepsilon bzdz + 2\int_{z_s}^{\frac{t}{2}} \left[\frac{\sigma_s}{\sqrt{1-\mu+\mu^2}} + K\left(\varepsilon - \frac{\sigma_s}{E}\right)^n\right] bzdz \quad (3)$$

b is the plate width, t is the plate thickness, Z_s is the distance from the initial yield surface to the neutral layer.

After unloading the bending moment [16]:

$$\frac{\kappa_1}{\kappa_0} = \frac{\kappa_0 - M/(EI)}{\kappa_0} = 1 - \frac{2z_s M}{tM_e} \quad (4)$$

κ_1 is the curvature after springback, κ_0 is the curvature before springback, I is the moment of inertia of the section, M_e is the maximum elastic bending moment.

From (3) and (4), we can obtain the formula for the curvature before springback [16]:

$$\kappa_0 = \kappa_1 \left[1 - 3\lambda + 4\lambda^3 - \frac{3A\sigma_s^{n-1}\left(1-2\lambda\right)^{n+1}\left(n+2\lambda+1\right)}{D^{n-1}E^n\left(2\lambda\right)^{n-1}\left(n+1\right)\left(n+2\right)} \right]^{-1} \tag{5}$$

$$\lambda = z_s / t\,,\, D = \sqrt{1-\mu+\mu^2}$$

A further correction fit to the compensated profile was made using the cubic B spline method [17]:

$$P(u) = \sum_{i=0}^{3} P_i N_{i,3}(u) = \frac{1}{6}\begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix} \tag{6}$$

P_i is the control vertex, $N_{i,3}$ (u) is the cubic B-sample basis function.

4. MULTI-POINT FORMING FINITE ELEMENT MODEL

The model data file of the hyperbolic component is imported into the multi-point 3D modeling software MPFCAD, and the punch height is obtained by determining the forming area and calculating the surface points, and the upper and lower punch envelope shapes are generated by importing into the finite element numerical simulation software.

Since there is an unloading process after the multi-point forming process of the hyperbolic member, the finite element model of the multi-point forming of the hyperbolic member is calculated by a combination of dynamic explicit and static implicit methods, that is, the loading multi-point forming process is calculated by using the dynamic explicit algorithm of the finite element analysis method, and then the unloading springback process is numerically simulated by combining the static implicit algorithm [18, 19].

Figure 6 shows the multi-point forming finite element model, which consists of upper and lower multi-point punch dies, upper and lower polyurethane elastic pads, and corrosion-resistant aluminum alloy plates. Since the deformation of the upper and lower multi-point punch dies is negligible compared with the elastic pad and plate during the multi-point forming process of the hyperbolic member, and in order to improve the calculation speed and save time, only the ball crown part of the upper and lower multi-point punch dies are retained and set as rigid bodies. Polyurethane (PU) is a super-elastic polymer material with good oil resistance, wear resistance and impact resistance, especially good elasticity, and can recover quickly after being extruded and deformed by external forces, therefore, the presence of polyurethane elastic pad in the multi-point forming process of double-bending component will greatly improve the contact state between the plate and multi-point punching die, and improve the point contact between multi-point punching die and plate to multi-point punching die The point contact is changed to surface contact, which greatly improves the force state of the sheet and prevents the indentation defects on the surface of the sheet, and obviously improves the forming quality [20].

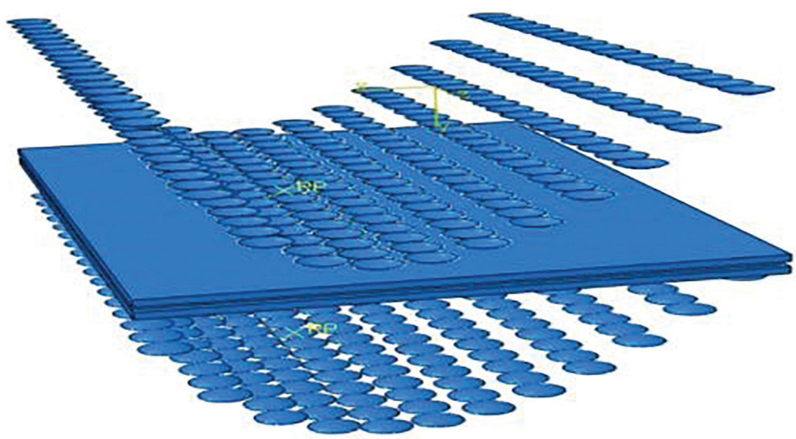

Figure 6: Multi-point forming finite element model.

The upper and lower multi-point punch dies are meshed with R3D4 cells, and the mesh cell size is 2.5 mm. The corrosion-resistant aluminum alloy sheet is divided into a grid using S4R cells with a grid cell size of 1.5 mm. The polyurethane elastic pad is divided into a grid using C3D8R cells with a grid cell size of 2.5 mm.

Considering the actual situation, the friction factor between the polyurethane elastic pad and the plate and the multi-point punch die is taken as 0.15.

5. ANALYSIS OF NUMERICAL SIMULATION RESULTS

After the finite element simulation calculation, the extracted data paths were established in two variable curvature edges BC and DA as feature lines on the formed hyperbolic member, respectively, and the numerical simulation results before and after compensated springback were extracted along the data paths for contour comparison with the target shape, as shown in Figure 7a and 7b.

The black curve is the profile of the formed part without springback compensation (i.e., before compensation), the red curve is the profile of the formed part with springback compensation (i.e., after compensation), and the blue curve is the profile of the target part.

It can be seen from Figure 7: the contour line of the formed part before compensation is too straight on both sides, the deformation is small, the difference between the curvature and the contour of the target part is too large, and the difficult problem of forming the variable curvature of the corrosion-resistant aluminum alloy hyperbolic member in the edge line BC and DA is not solved. The profile of the compensated formed part is more rounded and almost matches the profile of the target part, which better realizes the shape characteristics of the variable curvature of the corrosion-resistant aluminum alloy hyperbolic member in the edge line BC and DA.

On the edge line BC, the maximum error between the formed part and the target part contour before compensation is about 8.2 mm, and the maximum error between the formed part and the target part contour after compensation is no more than 1.6 mm, and the error is reduced by about 80%. On the edge line DA, the maximum error between the formed part and the target part contour before compensation is about 5.5 mm, and the maximum error between the formed part and the target part contour after compensation is not more than 1.4 mm, and the error is reduced by about 75%.

To sum up, the springback compensation of the hyperbolic member of corrosion-resistant aluminum alloy can realize the curvature characteristics of the target shape to a greater extent and reduce the springback error. In the case of compensated springback, the simulated shape of the springback corrosion-resistant aluminum alloy hyperbolic member is in good agreement with the target shape.

6. TEST VERIFICATION AND COMPARISON

The multi-point forming test was conducted on a multi-point forming press (shown in Figure 8) for the corrosion-resistant aluminum alloy hyperbolic member. The plate size, multi-point forming press parameters and test conditions were the same as those of the numerical simulation.

At the end of the multi-point forming test, the resulting formed test piece is shown in Figure 9.

Scan 3D laser scanner was used to scan the formed test part to obtain the point cloud data model. The point cloud model and the target shape were imported together into GOM Inspect software for analysis and comparison, and the error distribution cloud map shown in Figure 10 was obtained.

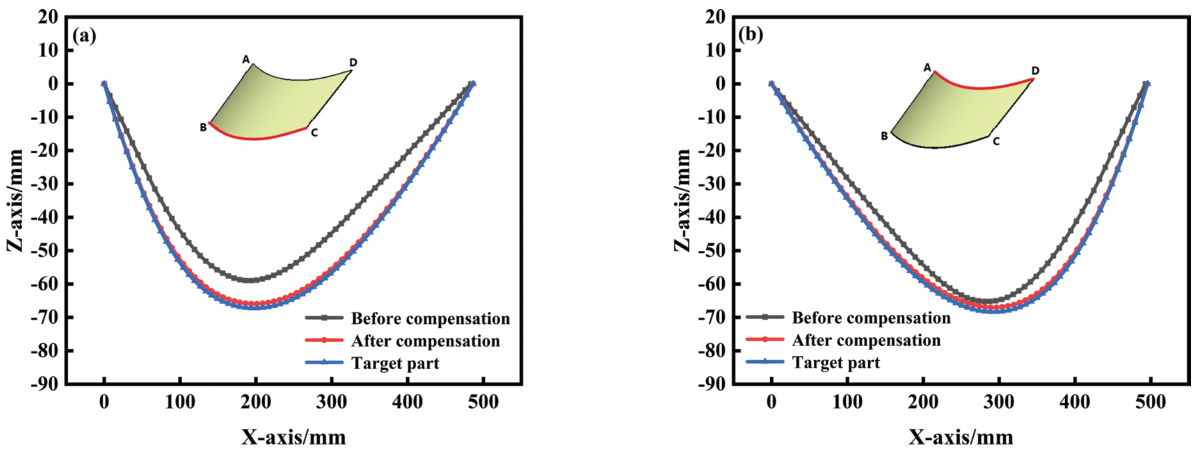

Figure 7: Feature line contour shape comparison.

Figure 8: Multi-point forming press.

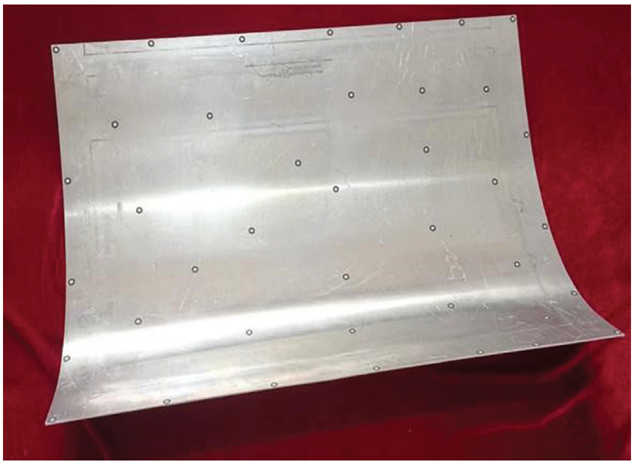

Figure 9: Test parts after forming.

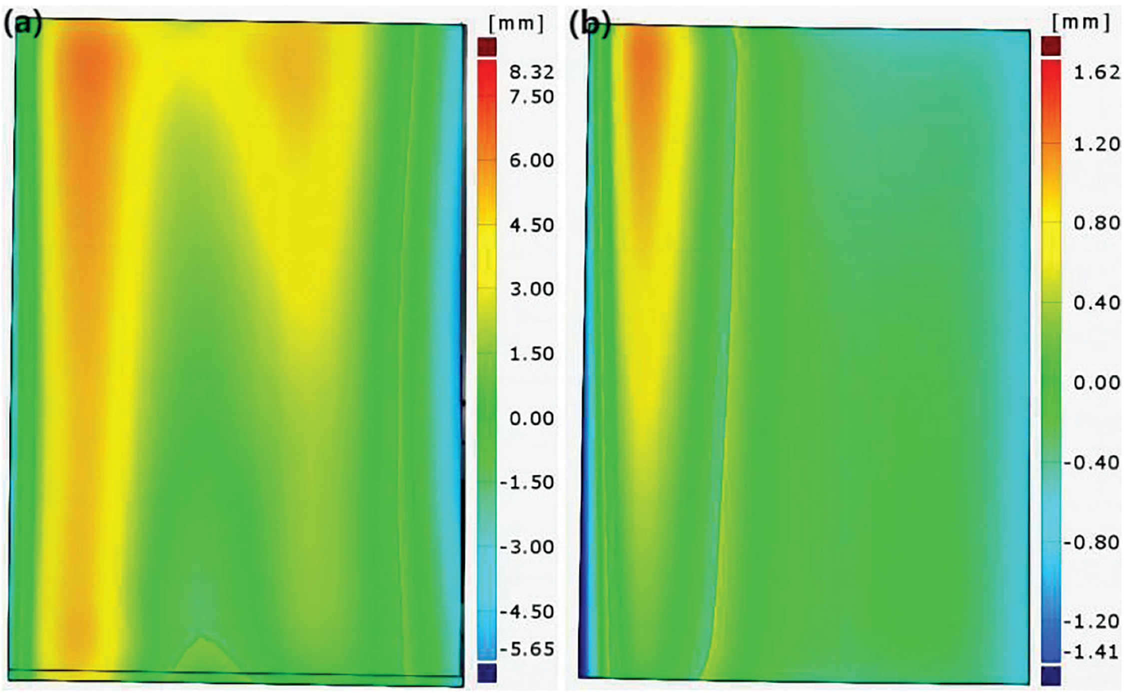

Figure 10: Error distribution cloud of test parts.

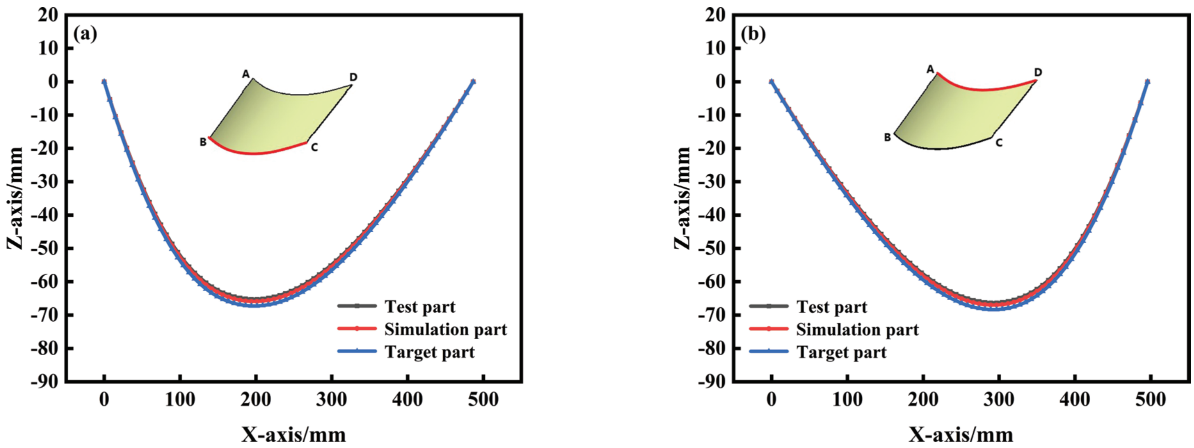

Figure 11: Feature line contour shape comparison.

As can be seen from Figure 10, the error range of the formed test piece before springback compensation is between –5.65 mm and +8.32 mm, while the error range after springback compensation is between –1.41 mm and +1.62 mm, with a maximum error reduction of nearly 80%.

Figure 11 shows the comparison of the characteristic line profile of the simulated formed part, the tested formed part and the target part after springback compensation. It can be seen from the figure that the simulated and tested results with springback compensation almost match with the target shape, and the springback error in the multi-point forming process of the corrosion-resistant aluminum alloy hyperbolic member is reduced more effectively, and the shape characteristics of variable curvature of the target shape are also realized better, which meets the engineering requirements of the target shape.

7. CONCLUSIONS

(1) Compared with the common aluminum alloy material, the corrosion-resistant aluminum alloy material calculated and tested in this paper has a smaller modulus of elasticity, and the springback of the formed part is larger after multi-point forming, therefore, a larger amount of springback compensation should be given in the calculation and modeling.

(2) Numerical simulations and forming tests were conducted to verify the springback compensation method proposed in this paper, and it was found that the simulation and test results after springback compensation are closer to the target shape with less error, which can realize the shape characteristics of variable curvature of corrosion-resistant aluminum alloy hyperbolic members to a greater extent and significantly reduce the number of forming times, which is a great guide to the actual multi-point forming production.

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