Theoretical and LS-DYNA® Analysis of Springback Effect on U-Shape Part Top Shape

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Abstract

In our AHSS U-Shape part springback study, small curvature on the U-Shape part flat top was observed after spring-back. Two mechanics models were used to explain the top bending and unbending deformation processes and the top curve forming mechanism. LS-DYNA simulation results and theoretical analysis results have good correlation. Based on the analysis, 5 methods were proposed to control the flat top spring-back.

Keywords: AHSS, Springback, Theoretical Analysis

Background

During our AHSS U-Shape part springback experiments and simulation, it was found out that there were small curvatures on the flat tops of the U-Shape parts (Figure 1). During the simulations, even though very high stretches were applied at the final stages of the U-Shape part draws, the top surfaces were looked like flat in the draws. However, the top surfaces shown curvatures after springback. Even though the curvatures are small, they can affect the contact areas of mating parts. In addition, the curvature can add to wall angle changes which may induce big displacement springback on side walls. Therefore it is meaningful to investigate the forming mechanism of the top curvature and to find out the control solutions.

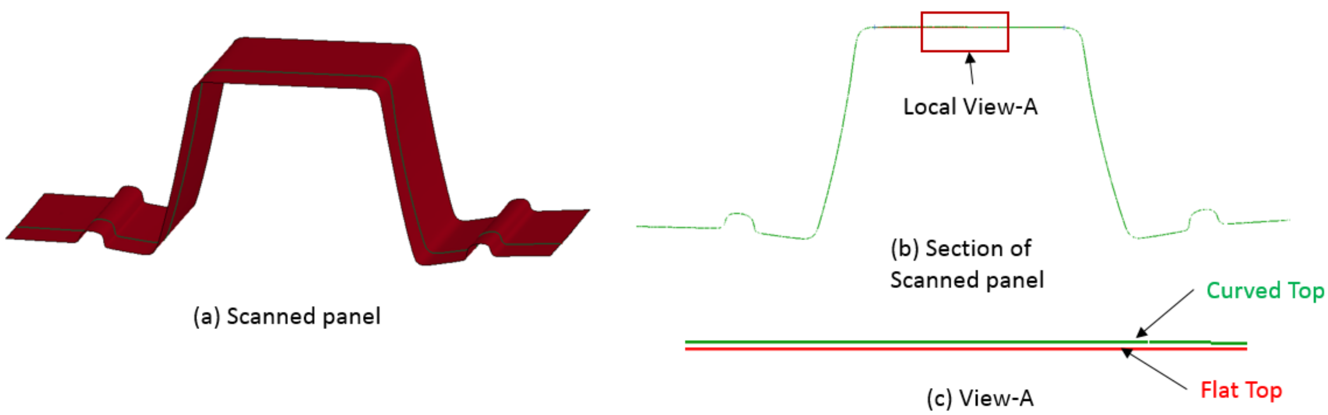


Figure 1. U-Shape part top curvature

Mechanics Models of U-Shape Part Top in Drawing

At the early stage of U-Shape part drawing, the top was bent to form an arc from the flat blank (Figure 2 in simulation). At the later stage, as the stretch stress increased, the arc top was pulled to flat or unbent to flat (Figure 3 in simulation). Therefore, during the U-Shape drawing process, the top was undergoing bending and unbending processes.

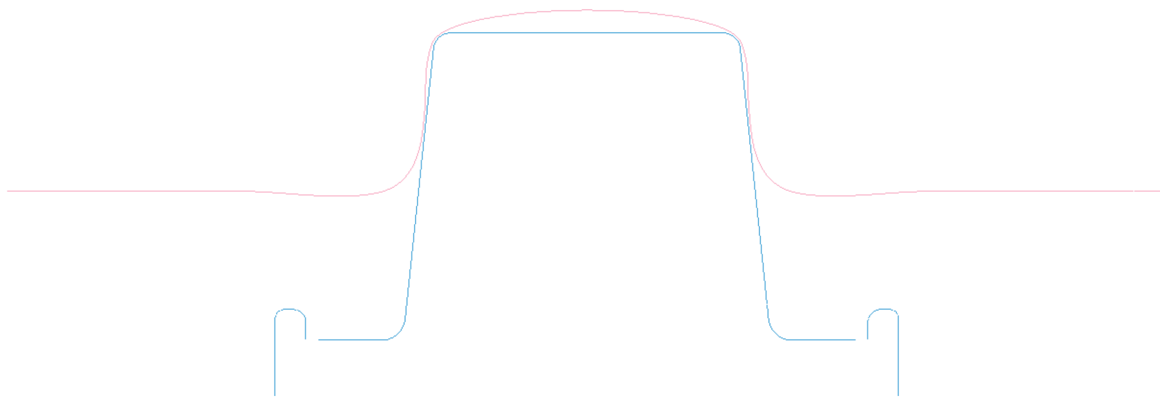


Figure 2. U-Shape part top bending curve

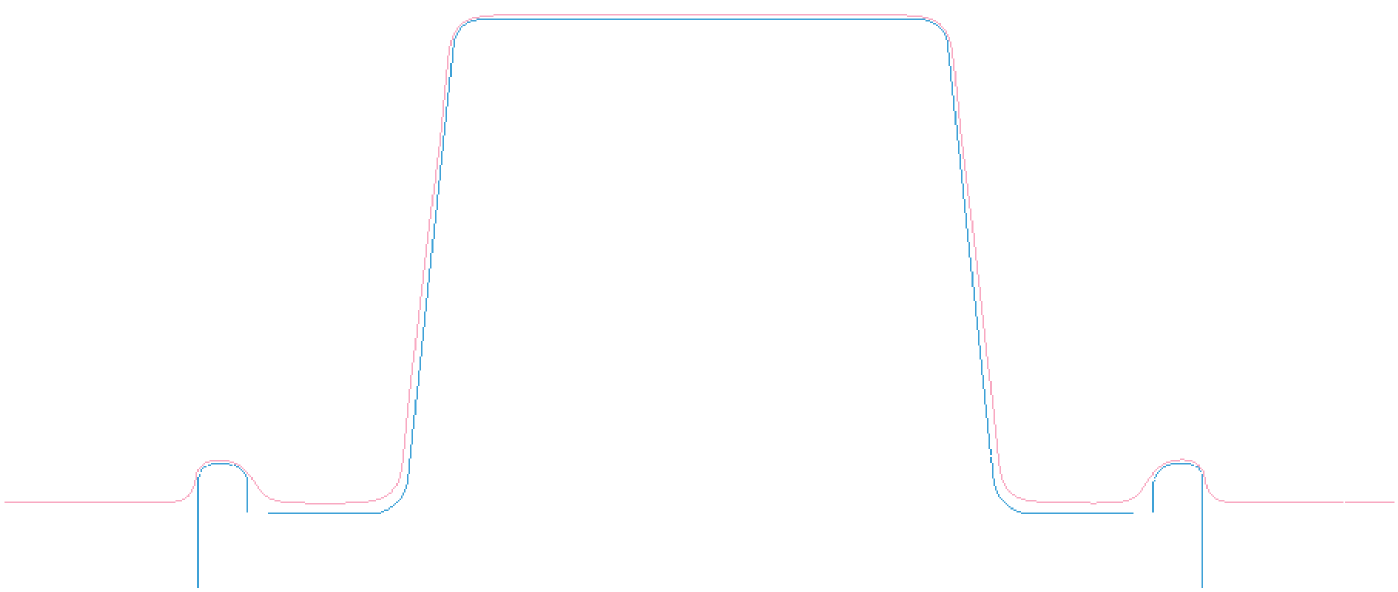


Figure 3. U-Shape part top un-bending flat

During the bending process, half of the top, from the top radius contact start point to symmetric plane, was cut off. Then, the mechanics model of the top half portion can be derived (Figure 4). On the symmetric plane - Plane-2, there are tensile force (F_2) and bending moment (M_2) and no shear force. On the contact start point plane - Plane-1, there are normal tensile force (F_{1n}), shear force F_{1t} and bending moment (M_1). Because this portion has no contact with other item, the resultant force (F_1) on Plane-1 will be equal to the force on Plane-2 (F_2).

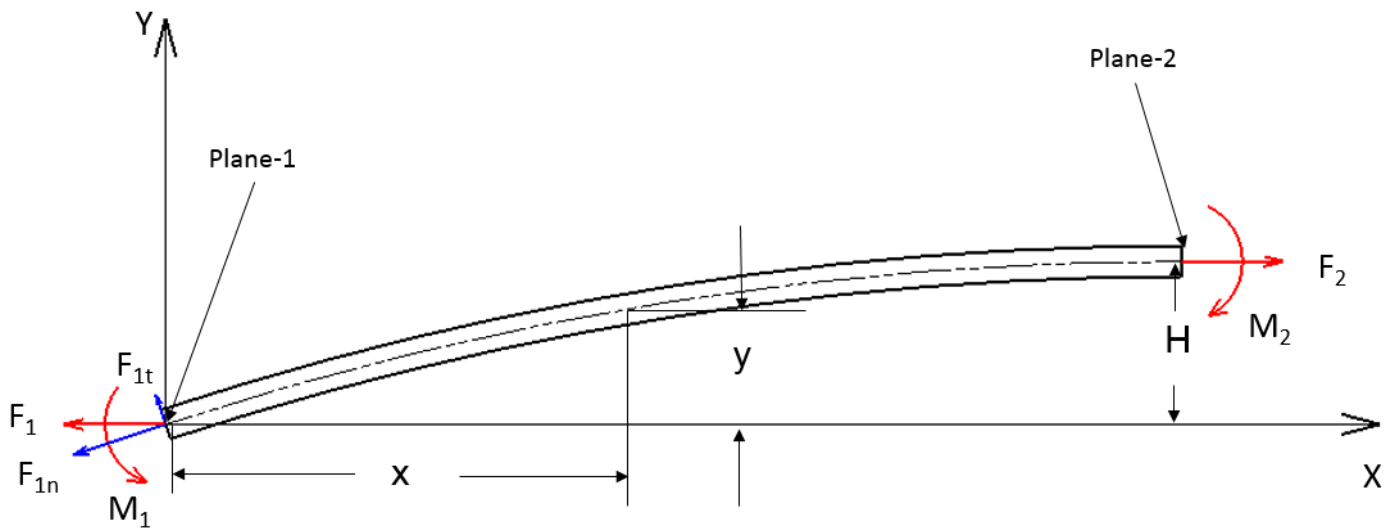


Figure 4. U-Shape part top mechanics model

$$F_1 = F_2 \qquad (1)$$

Now, on Plane-x, which is x away from Plane-1, the resultant force F_x and bending moment M_x are:

$$F_x = F_1 \qquad (2)$$

$$M_x = M_1 - F_1 \cdot y \qquad (3)$$

Therefore, the bending moment M_2 on Plane-2 is:

$$M_2 = M_1 - F_1 \cdot H \qquad (4)$$

Normally, the stretch force in metal sheet is small at the beginning of draw. In addition, when the stretch force is high, the formed arc of the U-Shape part top will be small. Therefore, the influence of the shear force on the U-Shape part top portion deformation can be neglected. The top area will be simplified as stretch bending model (Figure 5.).

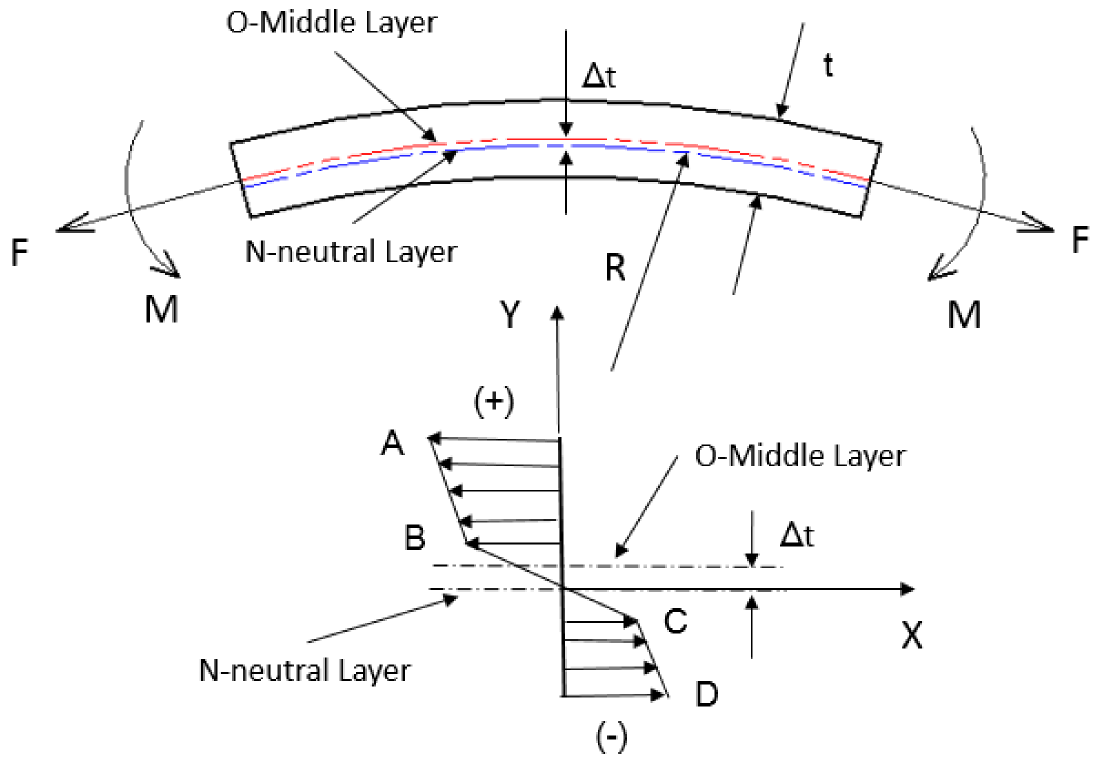


Figure 5. Stretch bending mechanics model

From the stretch bending model, if the neutral layer bending radius R and the neutral layer shift distance Δt are given, the strain along the bending direction can be calculated by equation (5):

$$\varepsilon = y / R \qquad (5)$$

Where y is the distance of one layer to neutral layer, and y is positive above the neutral layer, negative below it.

The outside layer strain is:

$$\varepsilon_{out} = (t/2 + \Delta t)/R \qquad (6)$$

The inner layer strain is:

$$\varepsilon_{in} = (t/2 - \Delta t)/R \qquad (7)$$

Equation (5) can be used both for plane strain and uniaxial stress conditions. To simplify the analysis, uniaxial stress condition is used in this paper. Plane strain condition will get the same conclusion. The difference between uniaxial stress and plane strain conditions is the amount of the stresses on bending direction.

From equation (5), based on the initial yield stress σ_0 of the material, it is easy to decide the elastic zone BC and plastic zones AB and CD. The stress distribution in elastic zone BC can be decided by using Hooke's Law:

$$\sigma = E \cdot \varepsilon \qquad (8)$$

Where E is Young's modulus.

The stress distribution on plastic zones AB and CD can be derived by using Swift law:

$$\sigma = K(\varepsilon_{pl} + \varepsilon_0)^n \qquad (9)$$

Where K is material hardening constant, ε_0 elastic strain constant, ε_{pl} plastic strain, and n is hardening exponent.

The stretch force F on the section is derived:

$$F = \int \sigma \cdot dy \qquad (10)$$

The bending moment about the middle layer is:

$$M = \int \sigma \cdot (y - \Delta t) \cdot dy \qquad (11)$$

When the neutral layer bending radius R and the neutral layer offset Δt are given, the stretch force F and the bending moment M can be derived by using Equations (10) and (11). In reverse, if F and M are given, R and Δt can be derived from equations (10) and (11).

In Figure 4, if the punch top radius is R_p, the minimum neutral layer radius on Plane-1 is:

$$R_1 = R_p + (t/2 - \Delta t) \qquad (12)$$

The maximum bending moment M_1 will be on Plane-1.

Top Metal Strain History

During the U-Shape drawing process, the top metal was undergoing bending and unbending processes. To simplify the explanation, a small portion of the top metal was selected (Figure 6).The deformation on this small portion is assumed to be uniform. In addition, engineering strain is used.

During the bending process, the outer layer of the metal was stretch ΔL_{ot1}, and the inner layer was compressed ΔL_{in1}. For stretch bending, $\Delta L_{ot1} > \Delta L_{in1}$, (see Figure 6).

The engineering strain during bending are:

$$\varepsilon_{ot1} = \frac{\Delta L_{ot1}}{L_0} \quad (13)$$

$$\varepsilon_{in1} = \frac{-\Delta L_{in1}}{L_0} \quad (14)$$

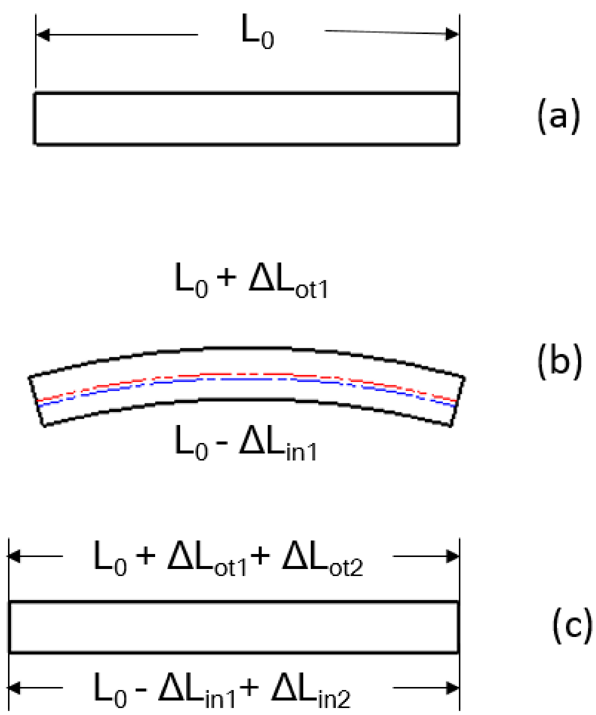


Figure 6. Bending and un-bending. (a) Before bending; (b) After bending; (c) After unbending

During unbending, as the stretch force is increased, the curved top metal is stretched to flat. The metal outside of the bending neutral layer is still under tension, so the metal in this zone does not have compression plastic deformation. When the stretch force is increased to certain level, the metal in this zone will have more stretch deformation.

The metal inside of the bending layer is change from compression to tension. The metal in this zone is undergoing stretch deformation during unbending. The outer layer and inner layer are used to explain the unbending process.

During unbending, the outer layer has stretch $\Delta L_{ot2,}$ and the inner layer has stretch ΔL_{in2}. The engineering strains for unbending are:

$$\varepsilon_{ot2} = \frac{\Delta L_{ot2}}{L_0} \qquad (15)$$

$$\varepsilon_{in2} = \frac{\Delta L_{in2}}{L_0} \qquad (16)$$

From Figure 6, it can be derived:

$$\Delta L_{in2} = \Delta L_{ot1} + \Delta L_{ot2} + \Delta L_{in1} \qquad (17)$$

Sprung Top Curvature Forming Mechanism and Control Analysis

From bending and unbending strain history (Equation (13)-(17)), it is derived: $\varepsilon_{in2} > \varepsilon_{ot1} + \varepsilon_{ot2}$. Therefore, it is easy to understand that the equivalent strain of the inner layer is bigger than that of the outer layer.

$$\bar{\varepsilon}_{in1} + \bar{\varepsilon}_{in2} > \bar{\varepsilon}_{ot1} + \bar{\varepsilon}_{ot2} \qquad (18)$$

Therefore, after unbending, the inner layer will have higher tension stress than the outer layer.

During springback, the inner layer will contract more than the outer layer. Hence, the top of U-Shape part will form a convex curve shape after springback. The theoretical springback amount can be calculated by using the integration mothed in Qin [1].

Theoretically, once the top metal of the U-Shape part experienced the bending and unbending, it is impossible to eliminate the top curvature after springback. However, some methods can be used to reduce the sprung curvature or to eliminate it.

Method 1: Increase the stretch force F at the early stage of the U-Shape part draw process.
From U-Shape part top mechanics model and stretch bending mechanics model (Figure 4, 5), when F is increased, Δt will increase, and the bending moment M on the section will decrease. Then the compressive strain ε_{in1} on the inner layer will be reduced during bending. The formed curvature during bending will be reduced accordingly.

During bending and unbending, the total length changes are similar to the equivalent stain changes.
From Equation (17), the total length change difference between inner layer and outer layer is:

$$(\Delta L_{in1} + \Delta L_{in2}) - (\Delta L_{ot1} + \Delta L_{ot2}) = 2 \cdot \Delta L_{in1} \qquad (19)$$

Therefore, when ΔL_{in1} is reduced, the equivalent strain difference between the inner layer and the outer layer will be reduced after unbending (equation 19). The stress distribution from the inner layer to the outer layer will be more even. Therefore, when stretch force F is increased, the sprung curve of the U-Shape part top will be reduced.

Method 2: Increase the stretch force F at the late stage of the U-Shape part draw process.
When the stretch force F at the late stage of the U-Shape part draw process is increased, the unbending stretch ΔL_{ot2} is increased. This will not reduce the equivalent strain difference between the inner layer and the outer layer. However, according to AHSS material hardening curves, for the same amount of equivalent strain difference, the stress difference at high strain zone is less than that at lower strain zone.

Hence, when the stretch force F is increased, the top metal strain level will be increased and the stress difference between inner layer and outer layer will be reduced. The sprung curve of the U-Shape part will be reduced.

Method 3: Increase the punch top radius R_p .
From equations (5)-(11), when R_p is increased, the bending moment on the top of the U-Shape part will be reduced. That is ΔL_{in1} will be reduced. Therefore, the sprung curve of the U-Shape part will be reduced.

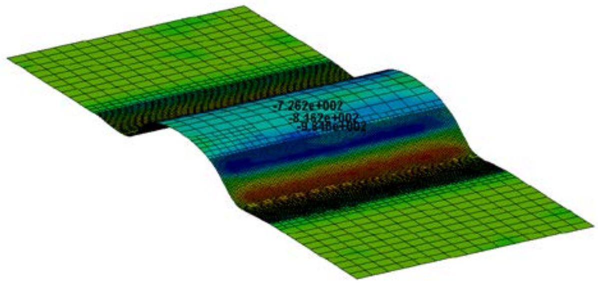
In addition, for the same top radius, when the material yield stress is increased, M_1 will increase and bigger top bending curve will be formed. This is why the higher the yield stress, the bigger the top bending curve. The top bending curves of AHSS materials are bigger than that of mild steels.

Method 4: Use upper flat pad.
When the upper pad is used, the top of the U-Shape part will be hold flat during the draw. The top bending process will be eliminated. The top of the U-Shape part will not have sprung curve. This method has been used in production for a while.

Method 5: Use compensate shape.
Based on the top bending and unbending mechanics models, compensate shape may be used to achieve flat top of U-Shape draw part.

Simulation Results Correlation

From above mechanics models, it is known that the maximum bending moment is on Plane-1 (M_1), and the minimum bending moment is on Plane-2 (M_2). During bending, the tension stresses on the outer layer are bigger than the compressive stresses on the inner layer in value. The middle layer stresses are tension stresses. Here are one simulation bending results.



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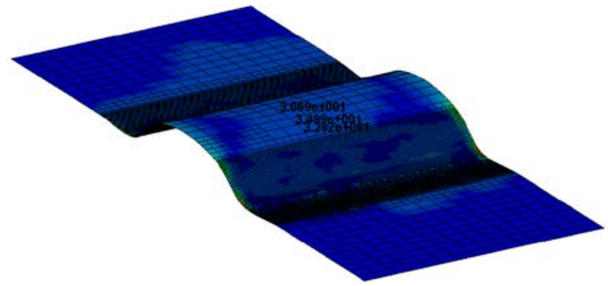

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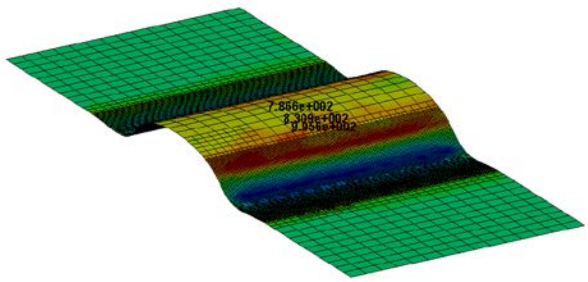
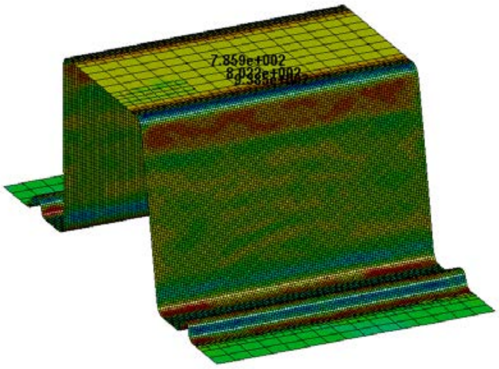


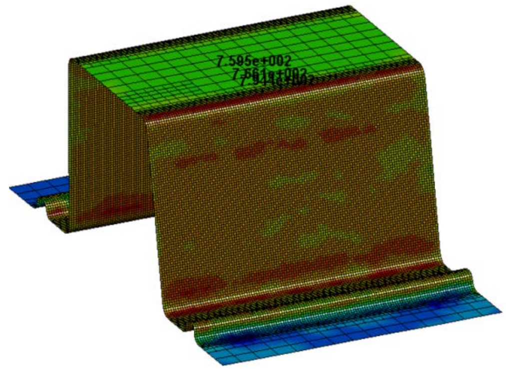
(c)

Figure 7. Top simulation stress distribution in bending
(a) Inner layer stresses;
(b) Middle layer stresses;
(c) Outer layer stresses;

The stresses on three layers with respect to three nodes from top radius to center plane are: inner layer (-984.6, -816.2, -726.2), middle layer (329.2, 349.9, 306.9), and outer layer (995.6, 830.9, 786.6). This stress distribution is correlated with theoretical analysis.
The simulation stresses after unbending are: inner layer (938.5, 802.2, 785.9), middle layer (794.4, 766.1, 759.5), and outer layer (375.2, 566.2, 604.1)



(a)



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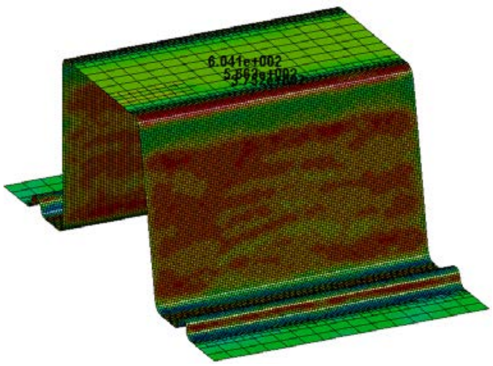

(c)

Figure 8. Top simulation stress distribution after unbending
(a) Inner layer stresses;
(b) Middle layer stresses;
(c) Outer layer stresses;

After unbending, the inner layer stresses are bigger than the corresponding outer layer stresses. This simulation stress distribution is correlated with theoretical analysis.

Conclusion

- By using the mechanics models provided in this paper, it can clearly show the U-Shape part top bending and unbending deformation processes during the draw.
- The U-Shape part top bending deformation can cause strain distribution uneven along the thickness and the final stress distribution uneven. Therefore, the top bending is the main reason that cause the top sprung curve.
- 5 methods are proposed to improve the top sprung curve.
- Based on Method 1 and 2, variable binder forces can be used to control the top sprung curve more efficiently.

References

[1] Z.G. Qin, A Study on the Springback Theory of Plastic Bending, Forging & Stamping Technology Vol. 20, No.1 (1995) 28-32