Anisotropic Behaviors and Its Application on Sheet Metal Stamping Processes

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ABSTRACT

Basic behaviors of anisotropic properties of materials, relating to sheet metal forming processes, are discussed. The R-value is used to describe some forming problems including wrinkles and thinning failures. According to the analysis results, to point out that the anisotropic behaviors of materials affect the formability of blanks in some cases is very serious. Finally, a numerical example is presented to discuss this property further.

INTRODUCTION

During sheet metal forming, anisotropic properties of a material usually exhibit two different forms. One is concerned with the hardening behavior when measured along two different directions on the plane of the sheet, meaning the relationship of the stress and strain is different in different directions due to the anisotropic properties of the material. Another anisotropic property is the different thinning values when measured along the plane of the sheet instead of through the thickness direction. These directional properties are all named as anisotropic properties of materials. Because the properties are defined as the abilities of materials to keep a high location of a forming limit diagram (FLD), to resist thickness change and to decrease wrinkle failures, that means different anisotropic properties will lead into different forming results and formability.

In this paper, we only discuss different thinning behaviors depended on the anisotropic properties and the R-values of materials in a required direction commonly used to describe these problems during sheet metal forming. As a matter of fact, shape of yielding spaces, thinning of formed blanks and wrinkles are all basically depended on the R-values when the anisotropic properties of a material are present. So we describe the anisotropic problems just around the R-values.

APPROACH

Because of the anisotropic properties present, many characteristics based on the plastic deformation will be changed, such as the yielding curve, strain space, thinning and etc. These basic behaviors must be understood first, if users want to apply the anisotropic properties to enhance forming processes.

Stress and strain spaces depended on different R-values

In order to simplify analyses, suppose that the anisotropic properties of the material are the same in the plane of the sheet, but different from the through thickness. Hills' (1948) yield criterion is used to discuss the anisotropic properties of material, which is expressed by the following:

$$F(\sigma) = \sigma_i = \left[\sigma_{11}^2 + \sigma_{22}^2 - \frac{2R}{R+1}\sigma_{11}\sigma_{22} + 2\frac{2R+1}{R+1}\sigma_{12}^2 \right]^{1/2} \tag{1}$$

If we select $\sigma_{11}, \sigma_{22,} \sigma_{33}$ as the principal stresses, Eq. (1) can be rewritten by:

$$F(\sigma)=\sigma_i=\left[\sigma_{11}^2+\sigma_{22}^2-\frac{2R}{R+1}\sigma_{11}\sigma_{22}\right]^{1/2} \quad (2)$$

Figure 1 shows several changing yield curves due to the selection of different R-values under the complex stress components with the same effective stress.

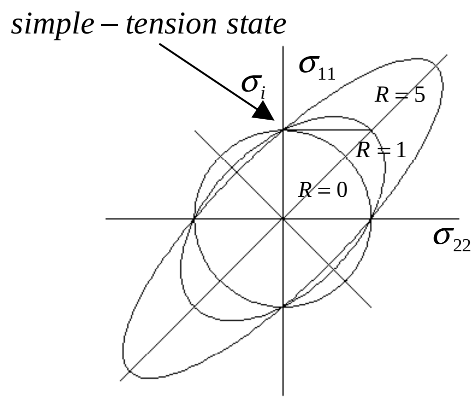


Figure 1. Stress space with different R-values

If the deformation theory of the stress and strain is selected to describe a strain space with two principal strains of sheet plan, the strain equation can be given by the following:

$$F(\varepsilon)=\varepsilon_i=\frac{1+R}{\sqrt{1+2R}}\left[\varepsilon_{11}^2+\frac{2R}{1+R}\varepsilon_{11}\varepsilon_{22}+\varepsilon_{22}^2\right]^{1/2} \quad (3)$$

This is a plane principal strain ellipse. With the same effective strain and several different R-values, several corresponding strain loci are shown in Figure 2.

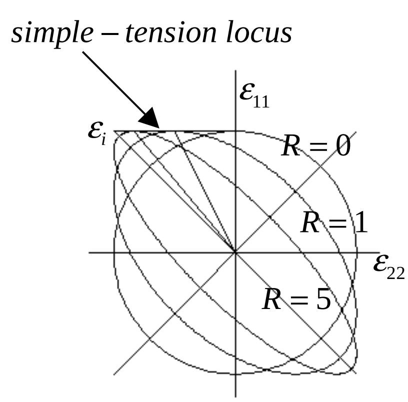


Figure 2. Strain space with different R-values

From points on Figure 1 and 2, we can classify some conclusions as follows:

a. Resistant forces of plastic deformation are increased with the bigger R-values when the stresses are distributed around two-stretch state.
b. Plastic deformations are easy to extract due to the bigger R-values in the stress state with one stretch stress and one compression stress.
c. The R-value is changed to be bigger, the deformation area combined a tension stress with a compression stress is smaller.

Strains behaviors relating to the wrinkle and thinning failures
If we want to use the anisotropic properties of materials to improve the formability of parts, we must know how the property behaviors are concerned with forming failures. Forming failures caused by the anisotropic properties usually are wrinkles and thickness thinning.

Wrinkles. Wrinkles are one type of forming failures. From a mechanics point of view, the wrinkles are caused by the compression instability, but not all the compression instability conditions result in the wrinkle failures during sheet metal forming. In fact, the wrinkle failures with many cases are mostly depended on the geometry of parts and material properties of blanks. If the geometry of parts and material properties of blanks are matched well, the wrinkle problems can be reduced fully. Now we discuss the wrinkle problems just around a deformation area in sheet plane with one elongation and compression.

When a deformation point on a blank is stretched into a die cavity during a stamping process, a stretching strain ε_{maj} and a planar strain $\varepsilon_{\min}$ in its vertical direction will be generated. Supposing $d(geo)$ is a geometry changing values at the same point and has the same direction as $\varepsilon_{\min}$. If the wrinkles are not be caused during the forming process, the strain state must satisfy the relationship shown below:

$$\varepsilon_{\min} = d(geo) \tag{4}$$

From Figure 2, we know that the $\varepsilon_{\min}$ value depends on the R-value with the same strain ε_{maj} and the same effective strain. According to Eq. (3) and the incompressible assumption of volume, the strain $\varepsilon_{\min}$ can be given as:

$$\varepsilon_{\min} = -\frac{R}{1+R}\varepsilon_{maj} - \frac{\sqrt{1+2R}}{1+R}\left(\varepsilon_i^2 - \varepsilon_{maj}^2\right)^{1/2} \tag{5}$$

When the deformation is a simple tension type, the effective strain ε_i is equal to the major strain ε_{maj}. The minor strain $\varepsilon_{\min}$ is:

$$\varepsilon_{\min} = -\frac{R}{1+R}\varepsilon_{maj} \quad \text{and} \quad tg\alpha = \frac{\varepsilon_{\min}}{\varepsilon_{maj}} = -\frac{R}{1+R}, \tag{6}$$

(simple tension type of deformation)

From Figure 3 and Eq. (6), we see that the all deformation areas with one tension and one compression stress will approach a point and become to the plane strain state when the R-value is close to zero or to infinity. That is:

$$\varepsilon_{\min} \to -\varepsilon_{maj}, \varepsilon_{thickness} \to 0, (R \to \infty)$$
$$\varepsilon_{thickness} \to -\varepsilon_{maj}, \varepsilon_{\min} \to 0, (R \to 0) \tag{7}$$

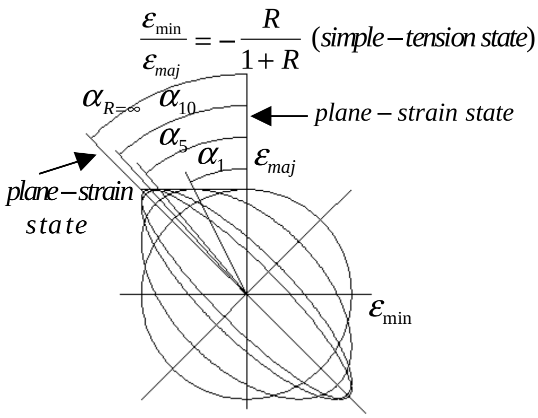


Figure 3. Strains varying with different R-values

The biggest changing area of the $\varepsilon_{\min}$ values is between the plane strain state and the simple tension state. In order to avoid the wrinkles caused during the stamping processes, the biggest R-value should be set up vertically around the biggest $d(geo)$ value direction as far as possible. If an optimal state can be set up on some cases, you should obtain an unexpected result. It is a very valuable work to use the anisotropic properties for improving the stamping processes, in particular for some special parts.

Thinning. In terms of the incompressible assumption of volume, we have:

$$\varepsilon_{\min}(\varepsilon_{22}) = -\varepsilon_{maj}(\varepsilon_{11}) - \varepsilon_{thickness}(\varepsilon_{33}) \tag{8}$$

Substituting Eq. (8) into Eq. (3), an equation related with the major strain and thickness strain is shown as:

$$\varepsilon_i = \frac{1+R}{\sqrt{1+2R}}\left[\frac{2}{1+R}\varepsilon_{11}^2 + \frac{2}{1+R}\varepsilon_{11}\varepsilon_{33} + \varepsilon_{33}^2\right]^{1/2} \tag{9}$$

This is an ellipse equation also, which we named as a thinning ellipse. Its half long-axis A and half short-axis B are given respectively as:

$$A = \varepsilon_i\left[\frac{2(1+2R)}{(1+R)\left(3+R-\sqrt{(R-1)^2+4}\right)}\right]^{1/2}$$
$$B = \varepsilon_i\left[\frac{2(1+2R)}{(1+R)\left(3+R+\sqrt{(R-1)^2+4}\right)}\right]^{1/2} \tag{10}$$

Figure 4 displays the shapes of two ellipses ($\varepsilon_t - \varepsilon_{maj}$ ellipse and $\varepsilon_{\min} - \varepsilon_{maj}$ ellipse) with several different R-values.

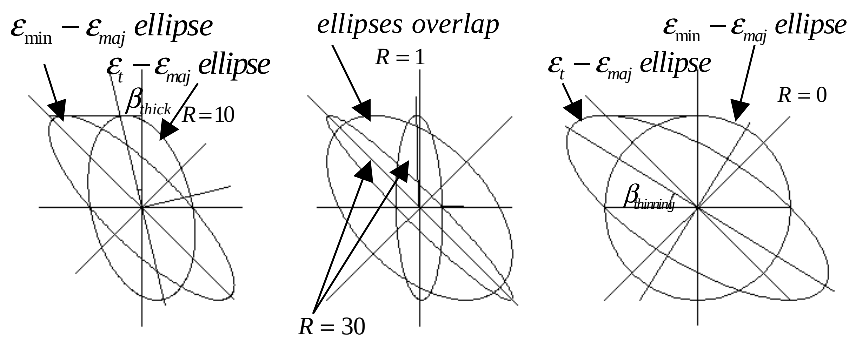


Figure 4. Thinning Behavior Based on Anisotropic Property

Rotation angles of the thinning ellipse compared with the principal strain ellipse in the sheet plane can be described by an equation below:

$$tg2\beta = \left|\frac{2}{R-1}\right| \tag{11}$$

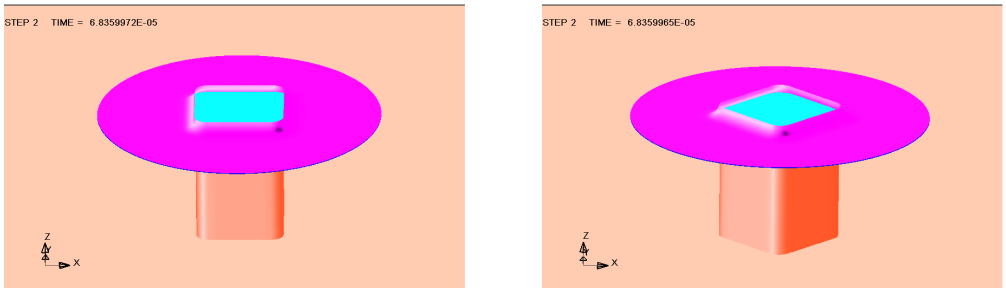
When the angle β is between the long axis of the ellipse with the ordinate, which is thickened angle β_{thick} associated with $R \geq 1$ and between the long axis of the ellipse with the abscissa, which means thinned angle β_{thin} associated with $R \leq 1$, they are shown in Figure 4 a, b and c.

According to the display in Figure 4, some rules concerned about strains varying can be concluded as follows:

a. The $\varepsilon_t - \varepsilon_{maj}$ ellipse rotates clockwise when the R-value is bigger than 1. The R-value is bigger, the rotation angle is smaller and the ε_t value is smaller.
b. The $\varepsilon_t - \varepsilon_{maj}$ ellipse and $\varepsilon_{\min} - \varepsilon_{maj}$ ellipse overlap with R=1, which means the ellipse equation with one ordinate value ε_{maj} vs. two abscissa values $\varepsilon_{\min}$ and ε_t;
c. The $\varepsilon_t - \varepsilon_{maj}$ ellipse rotates counter-clockwise when the R-value is smaller than 1. The thinning values increase faster with smaller R-values. The thinning value is biggest when R=0.

Numerical examples
FEA simulation for sheet metal forming can be used to easily calculate the forming results to repeat the set up to different material properties. Using the anisotropic properties of the materials, it commonly relates to that two main works to be done successfully, meaning: first, estimate the remaining capacity of the formed blank; second, select an optimal cropping shape based on the sheet rolling direction. The numerical example described in the following pages will discuss the anisotropic effects for calculating results depending on the set up of a blank with different positions based on the rolling direction.

Blanks, die and calculating results. Figure 5 shows forming tools and two blanks with a different rolling direction. The Y-coordinate is the rolling direction. Blank diameter is ϕ50 mm. Thickness is 0.5mm. Parameters of the anisotropic property are R_0=1.87, R_{45}=1.7 and R_{90}=0.17. The blank is formed by a square cup die twice, each time with a different holding force 15KN or 10KN. Final forming depth is 60mm. Figures 6 through 11 display some calculating results with different holding forces and drawing distances.



(a) Sample 1 (b) Sample 2

Fig.5 Blank shape with a different rolling direction set up

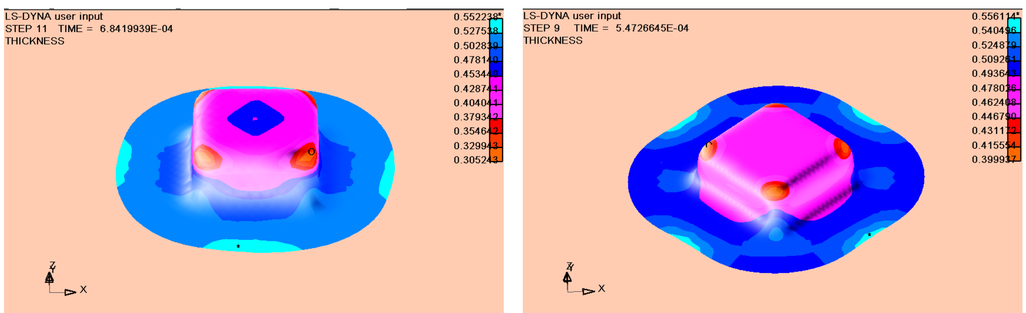


Fig.6 Forming results with a small drawing distance and small holding force

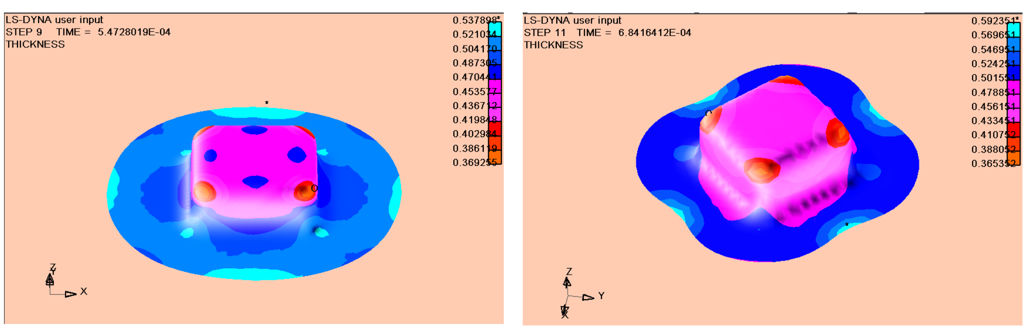


Fig.7 Forming results with a small drawing distance and big holding force

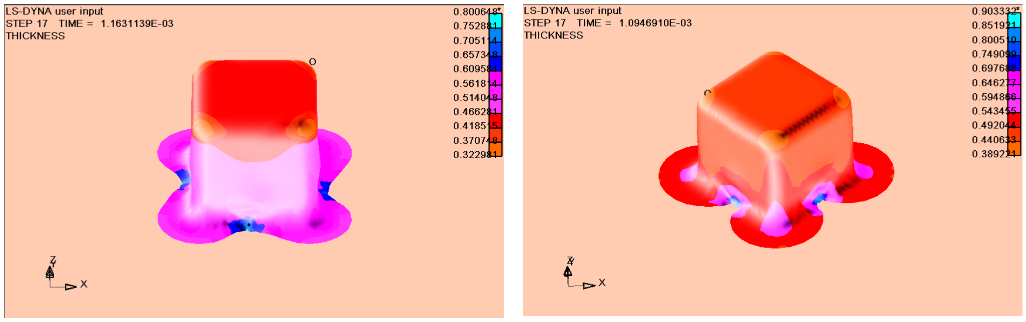


Fig.8 Forming results of the final step with a small holding force

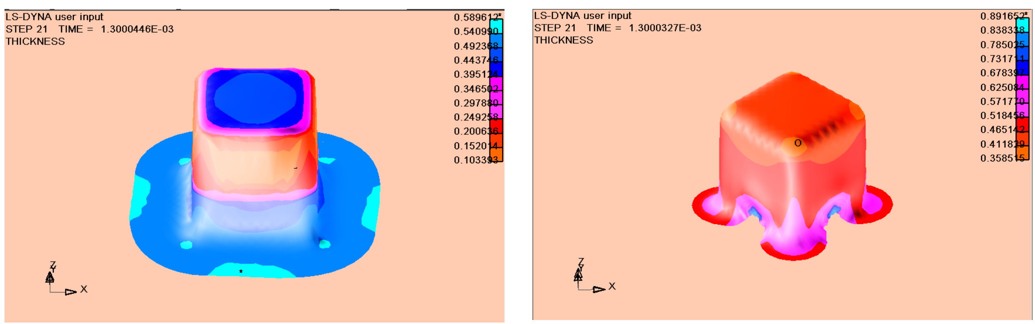


Fig.9 Forming results of final step with large holding force

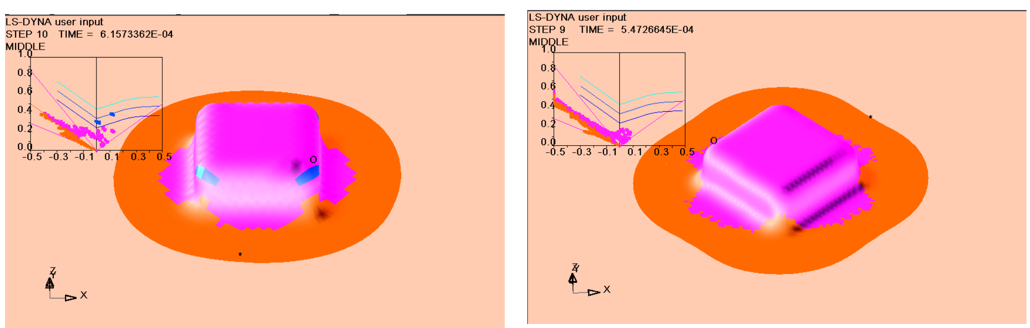


Fig.10 FLD with a small drawing distance and large holding force

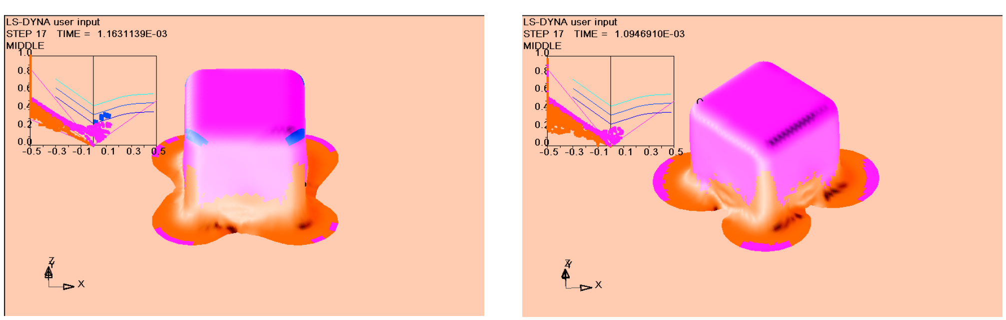


Fig.11 FLD of a final forming step with large holding force

DISCUSSION

From Figures 6 through 11, we notice a good formability can be obtained when setting up the largest R-value direction along the largest drawing force direction, that is along four turning corners (Sample 2). This is an area that plastic flowing of sheet metal is more difficult to determine. With this position, the thinning rate of the forming blank is smaller than another one, as well as the forming load. Due to its well formability, it is insensitive for some processing parameters, such as holding force, this blank also received satisfactory final results with two different holding forces. This property is very valuable for engineering production.

If the blank is set up in a different position based on the rolling direction, we received completely different forming results, see picture (b) in Figures 6 to 11. For this case, the larger R-values are set up on flat sides. Its formability is unsatisfactory. The plastic flow property becomes bad and the thinning rate of the blank increases. According to a result shown in Figure 10 (b), the punch moved a small distance and the part started to be split.

CONCLUSIONS

Almost all the sheet steels selected as the formed blank exhibit the anisotropic properties. The R-value can be used to describe their behaviors during forming processes, including yielding space, wrinkles and thinning failures. Some results are concluded as follows:

a. Resistant forces of plastic deformation are increased with the larger R-values when the stresses are distributed around two-stretch stress state.
b. Plastic deformations are easy to extract due to the larger R-values in the stress state with one stretch stress and one compression stress.
c. When the R-value is changed to be larger, the deformation area, combined a tension stress with a compression stress, is smaller.
d. If the wrinkles are not caused during the forming process, the changing rate of the blank geometry must satisfy the strain rate in the same direction at the same area.
e. The $\varepsilon_t - \varepsilon_{maj}$ ellipse can be used to describe the thinning behaviors. When it rotates in clockwise that means the R-value is larger than 1. The R-value is larger, the rotation angle is smaller and the thinning value is smaller. The $\varepsilon_t - \varepsilon_{maj}$ ellipse rotates in counter-clockwise that means the R-value is smaller than 1. The thinning values increase faster with smaller R-values. When R=0, the thinning value is biggest. The $\varepsilon_t - \varepsilon_{maj}$ ellipse and $\varepsilon_{\min} - \varepsilon_{maj}$ ellipse overlap with R=1, which means the ellipse equation with one ordinate value ε_{maj} vs. two abscissa values $\varepsilon_{\min}$ and ε_t.

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