Analysis of Flange Wrinkle in Square-shell Deep Drawing of Anisotropic Sheet

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An FEM simulation utilizing a dynamic explicit code was conducted to investigate the flange wrinkle behavior of square shell deep drawing of anisotropic steel sheets. In the FEM simulation, anisotropy of the r -value is taken account of by using the Barlat–Lian '89 equation. The yield locus diagram and the influence of anisotropy were investigated by changing the combination of the R_{00} , R_{45} and R_{90} value. One quarter portion of the 75 mm square punch and 80 mm square die was used in the simulation and frictional coefficient $\mu=0$ (Teflon lubricant condition) was adopted. As a result, the greater the m -value of the yield locus, the greater the yield stress (YS) and the greater the ΔCL value $(R_{90}-R_{00})/R_{ave}$ become, the bigger the flange wrinkle.

KEY WORDS: deep drawability; material draw-in; anisotropy; lubricant; FEM simulation; yield locus; r -value; square shell.

1. Introduction

Recently, Kuwabara^{1,2)} published review papers on the yield functions for anisotropic sheet metals, where several propositions, such as Hill '48³⁾ (quadric yield function), Goto⁴⁾ (biquadratic yield function) and Barlat–Lian '89⁵⁾ (m -degree yield function) were discussed. The authors *et al.*⁶⁾ have revealed, from the FE simulation using a static explicit code ROBUST, that the anisotropy of metal sheets has a significant influence on their formability. As for the testing method for deep drawability of sheet metals, the conventional Swift cup test of cylindrical deep drawing would not be sufficient for the evaluation of the formability for the real stamping products of square-shell or more complex shapes, such as automotive panels, bathtubs and several parts in IT industries. Thus the authors have reported the results of experiments and FEM analyses on the deep drawability^{7,8)} of square shells of highly anisotropic titanium sheets. One of the reports⁷⁾ experimentally revealed that material flow in direction L (the rolling direction) differs from that in direction C (the direction perpendicular to direction L) and that the apex of the flange corner shifts towards a smaller R -value in direction L. In this,⁷⁾ they also conducted an FE analysis with a dynamic explicit code (named code V) taking account for the Hill '48³⁾ (R -value) anisotropy, and found that the material flows in direction L and C are different, which corresponds to the experimental observations. However, there still remains some problems in accuracy of FE simulation, *e.g.* during the square-shell

deep drawing, the simulation predicts that the flange corner is strongly drawn in the direction of larger R -value, in contrast, in the experiment it flows in the smaller R -value direction.

Present report deals with an investigation of the relationship between material flow behavior and flange wrinkles based in the FE simulation with a dynamic explicit code (named code W). A square-shell deep drawing test was experimentally conducted using a 75 mm square punch and surface-treated steel sheets, and the tendency of wrinkle generation was compared with the result of the simulation. After confirming the accuracy of the computation model, FEM analysis was carried out using Barlat–Lian '89⁵⁾ yield function for various combinations of the in-plane anisotropies determined by the R -values in the sheet orientations of 0° (L), 45° (D) and 90° (C) as R_{00} , R_{45} and R_{90} . First, the effects of the in-plane anisotropy of the R -value and the exponent m of the yield function on yield locus were examined, and then the behaviors of flange wrinkle and material flow in the deep drawing of square shells were studied.

2. Square-shell Deep Drawing Experiment and Material Properties

A 75 mm square-shell deep drawing test was performed at the Steel Research Laboratories of Nippon Steel Corporation by using the punch and die set as shown in **Table 1**. The blanks were 200 mm square and the blank holding force (hereinafter abbreviated as BHF) was varied from 9.8

Table 1. Dimension of punch and die set.

Punch	Size	75mm square
	Shoulder radius	5mm
	Corner radius	8mm
Die	Size	80mm square
	Shoulder radius	5mm
	Corner radius	10.5mm

Table 2. Mechanical properties of material

Symbol	Thickness (mm)	YS (Mpa)	Parameters of equation (1)			r-value					
			K	ε_p	n	R_{00}	R_{45}	R_{90}	R_{ave} ^{*1}	ΔR ^{*2}	ΔCL ^{*3}
A	0.8	123	480	0.008	0.277	2.2	2	2	2.2	0.45	0.23
B	0.8	123	480	0.008	0.277	2	2	2	2	0	0
C	0.8	123	480	0.008	0.277	1.5	2	2.5	2	0	0.5
D	0.8	123	480	0.008	0.277	1.25	2	2.75	2	0	0.75
E	0.8	123	480	0.008	0.277	1	2	3	2	0	1
F	0.8	246	960	0.008	0.277	2.2	2	2.7	2.2	0.45	0.23

$$^{*1} R_{ave} = (R_{00} + R_{90} + 2R_{45})/4$$

$$^{*2} \Delta R = (R_{00} + R_{90})/2 - R_{45}$$

$$^{*3} \Delta CL = (R_{90} - R_{00})/R$$

Fig. 1. Relationship between plastic strain (ε_p) and true stress (σ).

to 98 kN. The stamping conditions when flange wrinkle occur were investigated by stamping experiments with Teflon film lubricant on upper and lower sides of blanks. Drawing ratio (hereinafter expressed as DR), which is the length of one side of the blank divided by the length of one side of the punch, was 2.67 (DR=2.67). The test specimen was 0.8 mm thick galvanized (GA) steel sheet, with mechanical properties as shown for Material A in Table 2. Because the work hardening properties of the material A were equal in the three directions, the Swift parameters in Eq. (1) were identified from the experimental data of direction L exclusively. The obtained result was used in the simulation performed using code W. The values K , ε_0 and n are listed in Table 2. Figure 1 shows the work hardening curve expressed by Eq. (1).

$$\sigma = K(\varepsilon_0 + \varepsilon_p)^n \quad \text{.....(1)}$$

While Table 2 shows the R -values in the three directions, it also defines the average R_{ave} of the R -values in the three directions and ΔR that are frequently used, together with ΔCL , which is the quotient of the difference between the R -value in direction L (R_{00}) and the R -value in direction C (R_{90}) divided by R_{ave} . The individual values were defined by Eqs. (2) to (4) given below.

$$R_{ave} = \frac{R_{00} + R_{90} + 2R_{45}}{4} \quad \text{.....(2)}$$

$$\Delta R = \frac{R_{00} + R_{90}}{2} - R_{45} \quad \text{.....(3)}$$

$$\Delta CL = \frac{R_{90} - R_{00}}{R_{ave}} \quad \text{.....(4)}$$

3. Outline of the Anisotropic Yield Function

Barlat-Lian '89⁵⁾ proposed the anisotropic yield function ϕ under plane stress condition by using equivalent stress σ_{eq} as shown in Eqs. (5) to (7). The parameters a , c and h in

Fig. 2. Effect of m -value on yield locus of Material A.

Eqs. (5) to (7), are given as functions of R -values R_{00} , R_{45} and R_{90} . The value of p is determined from the pure shear flow stress τ_{s1} and equivalent stress σ_{eq} . In this paper, the shape of yield locus is examined for $m=2, 4, 6$ and 8 .

$$\phi = a[K_1 + K_2]^m + a[K_1 - K_2]^m + c[2K_2]^m = 2\sigma_{eq}^m \quad \text{.....(5)}$$

where

$$K_1 = \frac{\sigma_x + h\sigma_y}{2} \quad \text{.....(6)}$$

$$K_2 = \sqrt{\left(\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2\right)} \quad \text{.....(7)}$$

$$a = 2 - 2\sqrt{\left(\frac{R_{00}}{1 + R_{00}}\right)\left(\frac{R_{90}}{1 + R_{90}}\right)} \quad \text{.....(8)}$$

$$c = 2 - a \quad \text{.....(9)}$$

$$h = \sqrt{\left(\frac{R_{00}}{1 + R_{00}}\right)\left(\frac{1 + R_{90}}{R_{90}}\right)} \quad \text{.....(10)}$$

While σ_x and σ_y are taken as the principal stresses, σ_x/σ_{eq} and σ_y/σ_{eq} are plotted as x and y axes. Figure 2 shows the effect of the value of m investigated using material A, whereas Fig. 3 shows the effect of the combinations of R_{00} , R_{45} and R_{90} investigated using assumed Materials B and E. The findings obtained were as follows:

(1) The yield locus of the commercial line product of material A differs little from that of perfect isotropic mate-

rial B.

(2) The effect of the value of m shows the same tendency as that pointed out by Barlat–Lian '89.⁵⁾ Namely in the first and third quadrants, where the absolute values of σ_x/σ_{eq} and σ_y/σ_{eq} became 1 or greater, the yield locus approached the point of origin (0,0) as the value of m increased.

(3) When ΔCL was large, as in material E with $R_{00}=1$, $R_{45}=2$ and $R_{90}=3$, the yield locus tilts more away from 45 degrees than isotropic material B with $R_{00}=R_{45}=R_{90}=2$.

4. Result of Three-dimensional FEM Analysis

4.1. Comparison with the Square-shell Deep Drawing Experiment

FEM analysis was conducted using a dynamic explicit code (named code W) taking into account the anisotropy, where the yield function Barlat–Lian '89⁵⁾ was used. The work hardening properties and R -values in the three directions of material A determined experimentally were adopted. At the same time, the dimensions of the punch and die and the deep drawing conditions were also matched to those used in the experiment. With symmetry in mind, however, analysis was only conducted in the one-quarter segment of the specimen. Because both surfaces of the blank were lubricated with Teflon, the frictional coefficient was assumed to be zero and the depth of drawing was set at 70 mm as in the experiment. While conducting simulation with different BHF matched to the experimental conditions, a value of m was chosen from among 2, 4, 6 and 8, in order to accomplish the best simulation of experimental wrinkles. In the square-shell deep drawing experiment, few wrinkles

Fig. 3. Yield locus in case of $m=2$ by Changing R_{00} , R_{45} , R_{90} value.

developed when the BHF was 49 kN. Figure 4 indicates the effects of the value of m with a BHF of 49 kN. Taking into account the fact that the simulation showed a tendency for wrinkles to diminish as the value of m became smaller, $m=2$ was adopted. While the paper of Barlat–Lian '89 proposed $m=8$ and $m=6$ for FCC and BCC metals respectively, $m=2$ or $m=4$ seemed more appropriate than 6 or 8 for material A (BCC metal) in the present study. However, Kuwabara's review²⁾ points out that there is a significant difference between the value reported by Hill '48³⁾ and the experimental value in the vicinity of equi-biaxial stretch region in SPCE cold-rolled steel sheets. Now that the yield function proposed by Barlat–Lian '89⁵⁾ agrees with that by Hill '48³⁾ when $m=2$, it seems necessary to conduct further studies, including the measurement of the yield function, in order to determine the appropriate value of m .

Figure 5 compares the wrinkles on the experimentally deep-drawn specimens and the result of their simulation. The results of simulation shown in Fig. 5 indicate that wrinkles grow larger with increasing BHF, which is in good accordance with the experimental results. Thus the simulation proved to be effective. Also, the flange wrinkles were larger near the corners and declined in size toward the center of the straight sides. While this was evidence of the conformance between the results of the experiment and those of the simulation, the length of the flange wrinkles near the corners were also close to that observed in the experiment. The reason why the wrinkles grew larger with an increase in the value of m will be discussed in the next chapter.

4.2. Effects of Yield Stress

A simulation was performed using an assumed material F with work hardening properties and R -values in the three directions equivalent to Material A and twice the amount of

Fig. 5. Influence of blank holding force (BHF) on flange wrinkle (upper side; experiment, lower side; simulation).

Fig. 4. Influence of m -value of Barlat–Lian '89 on flange wrinkle in case of BHF 29.4 kN (blank holding force) at Material A.

yield stress. **Figure 6** shows the effects of yield stress on the flange wrinkles thus determined. Material F developed wrinkles when the BHF was 29.4 kN, at which point material A, with a yield stress of 123 MPa, developed few wrinkles. In addition, material F developed slight wrinkles when the BHF was 49 kN, at which point material A developed no wrinkles, meaning the greater the yield stress, the more flange wrinkles developed, which correlated to conventional knowledge.

4.3. Effects of the Anisotropy of R -Value

The effects of the difference between the R -value in direction L (R_{00}) and that in direction C (R_{90}) was investigated using a material assumed to be analogous to material A in terms of work hardening properties, R_{ave} ($=2$) and ΔR ($=0$) but different in ΔCL . The value of ΔCL was 0 for the material B, 0.5 for the material C, 0.75 for the material D and

Fig. 6. Influence of yield stress (YS) on flange wrinkle.

Fig. 7. Influence of ΔCL value in case of blank holding force (BHF)=29.4 kN at forming height $h=63$ mm.

Fig. 8. Schematic illustration of deforming direction of Material B.

1.0 for the material E, respectively. Meanwhile the value of ΔCL for material A, used in the square-shell deep drawing experiment, was 0.23. With material E having a large ΔCL , analysis was possible only up to a deep drawing depth h of 63 mm, because the solution did not converge when the BHF was as small as 29.4 kN. With a BHF of 29.4 kN, therefore, the wrinkles on all specimens shown in **Fig. 7** developed at the same deep drawing depth h of 63 mm. Obviously, the flange wrinkles grew larger as the value of ΔCL increased. This relationship will be further discussed in the following chapter.

5. Discussion

5.1. Effects of the Value of m in the Anisotropic Yield Function on Wrinkles

The reason why flange wrinkles grow larger as the value of m in Eq. (5) increases as shown in Fig. 4 may be explained as follows: The vertical law of the plastic strain increment vector with respect to yield locus has been verified by experiments, as exemplified by Kuwabara *et al.*⁹⁾ **Figures 8 and 9** respectively show the directions of the plastic strain increment vector for the material A with $m=2$ and $m=8$ that were observed in a limited part of the first quadrant.

The plastic deformation of metal sheets is divided into stretching and drawing regions depending on the values of the biaxial plastic strains ϵ_x and ϵ_y , as indicated by the forming limit diagram (hereinafter expressed as FLD). Though the form of FLD differs between different literature, depending on which of $\epsilon_x=0$ or $\epsilon_y=0$ is chosen, the plane strain in this report is defined at $\epsilon_y=0$. The stretching regions, where both ϵ_x and ϵ_y are positive have an upper limit at $\epsilon_y=\epsilon_x$.¹⁰⁾ While according to many literatures the drawing regions have a lower limit at uniaxial tension

Fig. 9. Schematic illustration of deforming direction of Material A at $m=8$.

($\varepsilon_y = -0.5\varepsilon_x$),¹⁰⁾ some literature shows the lower limit at $\varepsilon_y = -\varepsilon_x$.¹¹⁾ Therefore, the lower limit in this report is set at $\varepsilon_y = -\varepsilon_x$.

Since the yield locus is considered to be the borderline between elastic deformation and plastic deformation, it may be presumed that the stress-strain relationship of elastic deformation holds until the yield locus is reached. In the case of an isotropic material, the elastic stress-strain relationship for the plane strain deformation are expressed by Eqs. (11) and (12).¹²⁾ If Poisson's ratio $\nu=0.3$, Eq. (12) gives $\sigma_y=0.42\sigma_x$ at plane strain deformation. In equi-biaxial deformation, $\sigma_y=\sigma_x$ was obtained at $\varepsilon_y=\varepsilon_x$, whereas under the lower limit of the drawing region, namely at $\varepsilon_y=-\varepsilon_x$, $\sigma_y=-\sigma_x$ was obtained.

$$\varepsilon_x = \frac{(1-\nu^2)}{E} \left(\sigma_x - \frac{\nu}{1-\nu} \sigma_y \right) \dots\dots\dots(11)$$

$$\varepsilon_y = \frac{(1-\nu^2)}{E} \left(\sigma_y - \frac{\nu}{1-\nu} \sigma_x \right) \dots\dots\dots(12)$$

In Figs. 8 and 9, point P shows the lower limit of drawing deformation at $\sigma_y = -\sigma_x$, point Q shows uniaxial tensile deformation, point R shows the plane strain deformation and point S shows equi-biaxial deformation. The segment between P and Q, where $\varepsilon_x > 0$ and $\varepsilon_y < 0$, is a drawing region, while that between Q and R is also a drawing region because tensile deformation occurs in direction X with $\varepsilon_x > 0$ and compression deformation occurs in direction Y with $\varepsilon_y < 0$. The segment between R and S is a stretching region because tensile deformation occurs in both directions X and Y with $\varepsilon_x > 0$ and $\varepsilon_y > 0$. Since it seems difficult for flange wrinkles to develop in the stretching region, although prone to occurring in the drawing region, the form of the yield locus between P and R is considered to affect the generation of flange wrinkles. Figure 8 implies that the direction in which plastic deformation proceeds changes smoothly when $m=2$, whereas in the case of $m=8$ (Fig. 9), the direction of plastic deformation seems to have a tendency to become biased because the yield locus involves straight segments that have inclinations of 45 degrees. Obviously, the segment between Q and R, where the yield locus becomes substantially straight when σ_x is approximately $1.2 \sigma_{eq}$, also involves a region where the direction of plastic deformation converges. Thus, the value of $m=8$ leads to the results that heterogeneous deformation and wrinkles are more liable to occur. **Figure 10** compares the distribution of shear flow stress τ_{xy} at depth $h=70$ mm with a BHF of 49 kN with $m=2$ and $m=8$. This figure shows that the ab-

solute value of the shear stress at the flange is somewhat greater, and the wrinkles at the flange are larger, with $m=8$ than with $m=2$.

5.2. Effects of ΔCL as Evaluation Index of Anisotropy of R -Value

The reason why wrinkles grow larger as the value ΔCL defined in Eq. (4) increases is discussed here. **Figure 11** shows how the deviation angle θ of the flange corner apex from the direction of 45 degrees changes with ΔCL when a BHF is 49 kN. **Figure 12**, which shows the relationship between ΔCL and θ , reveals that the angle θ and heterogeneous deformation increase as the value ΔCL increases. Thus, it follows that flange wrinkles grow larger as the value ΔCL increases. **Figure 13** shows this relationship examined by the difference of equivalent plastic strain in the early stage of forming. This figure compares the equivalent plastic strain in material B ($\Delta CL=0.0$) and material E ($\Delta CL=1.0$) at a forming depth of 7 mm with a BHF of 49 kN. In the early stage of forming, it seems apparent that the equivalent plastic strain in direction L with small R -value becomes greater when ΔCL increases. This indicates the occurrence of the heterogeneous deformation due to the predicted result that plastic deformation proceeds faster in direction L than in direction C. Thus, it follows that greater ΔCL leads to the formation of larger flange wrinkles. This also seems to provide an explanation for Fig. 11, in which the flange corner bends toward direction L, because yielding and plastic deformation occurs earlier at the smaller R -value direction L. In Fig. 13, the equivalent plastic strain, rather than shear stress, was selected because plastic deformation behavior in the early stage of forming has a significant influence on ΔCL . The report⁷⁾ of a study on the material flow of titanium sheet made by the authors shows that the flange corner apex bends toward direction L where the R -value is small (**Fig. 14**). This corresponds to the result of

Fig. 10. Shear stress τ_{xy} distribution incase of BHF=49 kN at forming height $h=70$ mm.

Fig. 11. Measuring method of deviation angle θ of flange corner by changing ΔCL value at blank holding force (BHF) 49 kN.

Fig. 12. Relationship between ΔCL and deviation angle θ .

Fig. 13. Equivalent plastic strain distribution in case of BHF=49 kN at forming height $h=7$ mm.

Fig. 14. Photograph of the formed square shell of titanium sheet ($R_{00}=1.6$, $R_{45}=3.2$, $R_{90}=7.0$).

the present simulation shown in Fig. 11. The value of ΔCL for the titanium sheet derived from Eq. (4) is 1.44, though the simple comparison with a titanium sheet might be impossible because anisotropy of the work hardening of titanium sheet is also apparent. Still, at least the direction in

which the flange corner apex bends may be to correspond to the experimental results.

6. Conclusion

The following findings were derived from the present study on the relationship between the behavior of material flow in the flange and flange wrinkles in square-shell deep drawing simulation tests by employing an FEM analysis incorporating Barlat–Lian '89⁵⁾

(1) Flange wrinkles grow larger as the value of the yield function m used in Barlat–Lian '89⁵⁾ increases.

(2) Flange wrinkles grow larger as yield stress increases.

(3) Flange wrinkles grow larger as the value of ΔCL increased, where ΔCL is a new evaluation index to show the anisotropy of the R -value and the quotient obtained by dividing the difference between the R -value in direction L (R_{00}) and the R -value in direction C (R_{90}) by R_{ave} .

(4) When ΔCL increases, the flange corner bends in direction L with smaller R value.

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