ESTIMATION OF SPRINGBACK OF STAINLESS STEEL SHEET PART TAKING INFLUENCE OF ANISOTROPIC PROPERTY OF PLASTIC-DEFORMATION-DEPENDENT YOUNG'S MODULUS INTO ACCOUNT

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Key words: Sheet metal forming, Springback, Stainless steel sheet, Yoshida-Uemori model.

Abstract. A kinematic hardening model proposed by Yoshida and Uemori (Y-U model) was applied to the prediction of springback of stainless steel sheet part. From the experiments for the determination of the material constants, an anisotropic property of change in Young's modulus was observed; namely, the anisotropy was different at 0°, 45° and 90° from the rolling direction. The Y-U model for the stainless steel sheet was used to a calculation of a forming process of a part to examine the accuracy of the prediction of the springback by compar-ing the calculated result with the actual part formed. In order to consider the anisotropic property of change in Young's modulus, the calculated result to the actual part formed. In order to consider the anisotropic property of the change in Young's modulus, the calculations were performed using the different material constants at 0°, 45° and 90° from the rolling direction. With the material constants at 90° from the rolling direction, which was the direction of springback of the part, the prediction accuracy can be improved. Therefore, the consideration of the anisotropic property of the change in Young's modulus was found to be effective for more accurate prediction of the springback of the stainless steel part.

1 INTRODUCTION

Stainless steel sheets have been commonly used for automobile exhaust parts due to the excellent feature of corrosion resistance, heat resistance and design. The sheet metal part has become complicated in geometry and forming process due to the current demand of the strength and the lightness as an automobile part. Therefore, finite element analysis has widely used effectively nowadays for designing a sheet metal forming process. However, the precise prediction of springback has still been open problem. Many researches have been reported on the improvement of the accuracy. It is well known nowadays that the plastic constitutive model developed by Yoshida and Uemori (Y-U model) can furnishes more accurate prediction of springback in the case of sheet metal forming of high-strength steel than conventional isotropic or kinematic hardening models in FE analysis [1-4].

In the present paper, the Y-U model was applied the part by stainless steel sheet for more presice prediction of the springback. First, the experiments of the materials were performed to determine the material constants used in the Y-U model. From the experiments, the anisotropic behavior of plastic-deformation-dependent Young's modulus in which the apparent Young's modulus decreases after preloading was confirmed in stainless steel sheet. Therefore, a method of calculation considering of the anisotropic property of the change in Young's modulus in Y-U model was examined by comparing the calculated results of springback with actual sheet metal part.

2 EXPERIMENTAL METHOD FOR TENSILE-COMPRESSIVE BEHAVIOR OF SHEET METAL

Several experiments have been reported for the tensile-compressive behavior of sheet metal without buckling under compressive loading [1, 5]. In the present paper, an electro-hydraulic controlled fatigue testing machine SHIMADZU Servopulser EHF-EV 100KN/TV 1KN/m-A20 was used for tensile-compressive tests of the materials. Figure 1 shows the geometry of specimen used for tensile-compressive tests. Figure 2 show Schematics of setup for tensile-compressive tests of stainless steel sheet. The specimen was clamped between clamp A, B and clamp C, D in order to prevent buckling. The extensometer SHI-MADZU SG10-100 was used with a jig shown in Figure 2 to measure the elongation of the specimen from the thickness direction without touching the clamps. The material used was SUS304 and SUS430. The angles of loading direction of the specimen were at 0°, 45° and 90°from the rolling direction (RD).

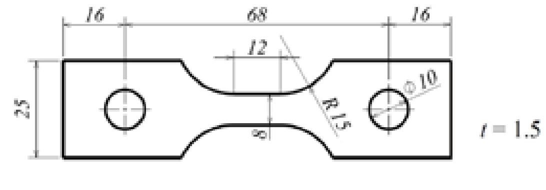

Figure 1: Geometry of specimen (unit: mm)

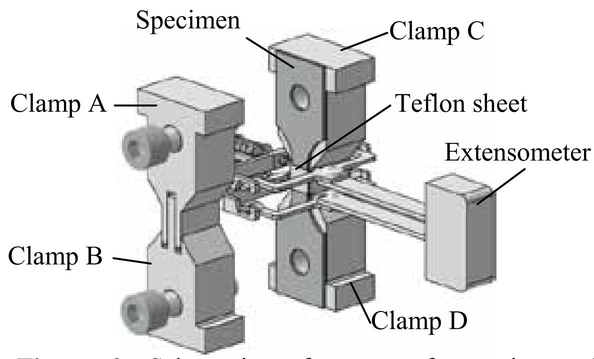

Figure 2: Schematics of setups of experiment for tensile-compressive tests of stainless steel sheet.

Figures 3 and 4 show experimental results of tensile tests of SUS304 and SUS430. Figure 5 shows a result of tensile-compressive loading test of SUS304, in which strain was subjected to 2.5%→-2.5%→5%→-5%. Figure 6 shows a result of loading-unloading tests of SUS304 for the evaluation of plastic-deformation-dependent Young's modulus.

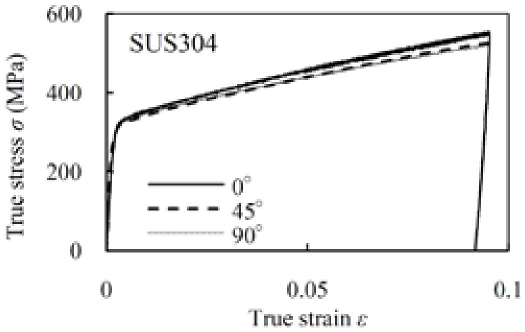

Figure 3: Stress- strain curves of SUS304 under tensile loading

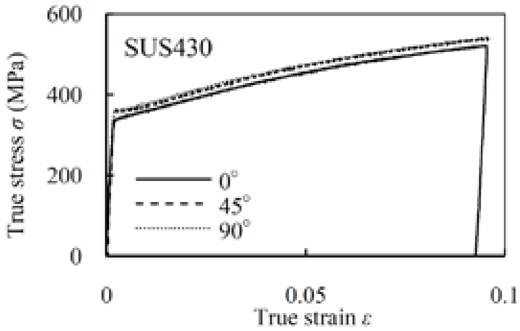

Figure 4. Stress-stain curves of SUS430 under tensile loading

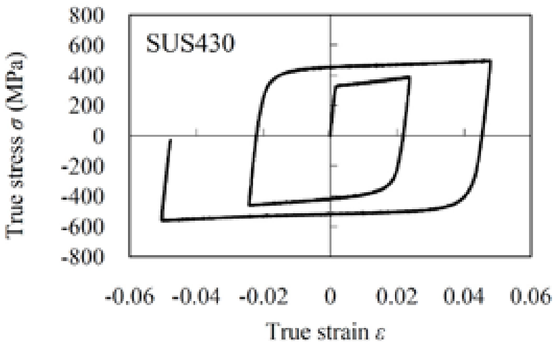

Figure 5. Stress-strain curve of SUS430 under tensile-compressive test

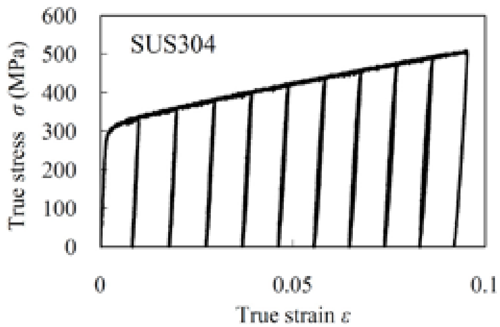

Figure 6. Result of loading-unloading tests of SUS304

3 ANISOTROPIC PROPERTY OF PLASTIC-DEFORMATION-DEPENDENT YOUNG'S MODULUS

Anisotropic property of plastic-deformation-dependent Young's modulus is a phenomenon in which apparent Young's modulus after plastic deformation decreases with the increase of equivalent plastic strain.

Figures 7 and 8 show the change in Young's modulus E_{av} as a function of equivalent plastic strain of SUS304 and SUS430. Moreover, for the sake of comparison, the change in Eav of high tensile strength steel sheet JSC980YN is shown in Figure 9. The stress range of stress used for the calculation of E_{av} was $0 \le \sigma \le 0.95\sigma_0$, where σ_0 is the stress from which the unloading began.

In case of JSC980YN, it seems that plastic-deformation-dependent Young's modulus is almost isotropic. In case of SUS304 and SUS430, however, the anisotropic behaviors in change in the E_{av} were observed obviously. For SUS430, the dependence tendency at 45° is the same as the tendency at 90°, only the tendency at 0° is different from the others. On the other hand, for SUS304, the different tendency was observed in the range of $0 \le \overline{\varepsilon^p} \le 0.04$ in each specimen. As the strain become larger, only the tendency of at 45° is different from at 0° and 90°.

In the Y-U model, the Eav can be given in the following expression using initial Young's modulus E_0 and its asymptotic value E_a:

$$E_{av} = E_0 - \left(E_0 - E_a\right)\left\{1 - \exp\left(-\xi \overline{\varepsilon^p}\right)\right\} \tag{1}$$

where, ξ is a material constant. Material constants for equation (1) at 0°, 45° and 90° from the RD were obtained as shown in Table 1.

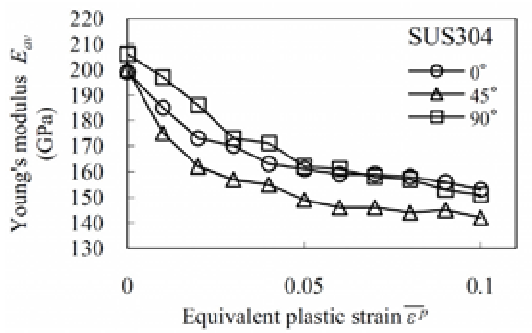

Figure 7: Change in plastic-deformation-dependent Young's modulus of SUS304

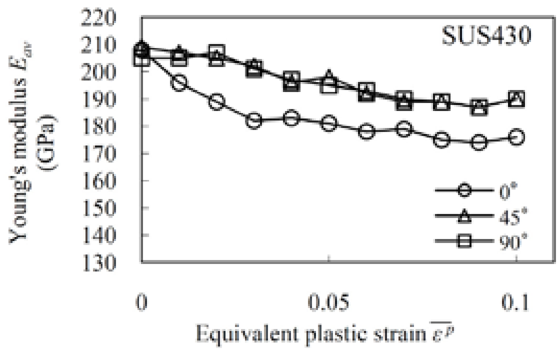

Figure 8: Change in plastic-deformation-dependent Young's modulus of SUS430.

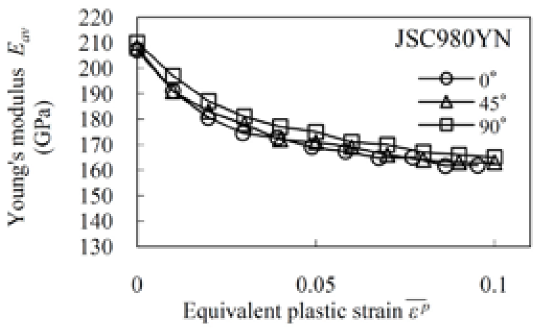

Figure 9. Change in plastic-deformation-dependent Young's modulus of JSC980YN.

Table 1: Material constants for change in Young's modulus

Material	Loading direction	E_0 (GPa)	E_a (GPa)	ξ
SUS304	0°	203	154	40
	45°	200	143	40
	90°	206	148	20
SUS430	0°	208	175	40
	45°	209	183	17
	90°	212	183	18

4 MATERIAL CONSTANTS OF HARDENING MODEL OF Y-U MODEL

In the present study, the calculation was performed using the Y-U model that can represent the work hardening stag-nation, plastic-deformation-dependent cyclic hardening and plastic-deformation-dependent Young's modulus. In Y-U model, the yield surface f and the bounding surface F are expressed by the following equation:

$$f = \phi\left(\boldsymbol{\sigma}, \boldsymbol{\alpha}\right) - Y = 0 \tag{2}$$

$$F = \phi\left(\boldsymbol{\alpha}, \boldsymbol{\beta}\right) - \left(B + R\right) = 0 \tag{3}$$

where ϕ is the function expressing equivalent stress, Y is the radius of f, $\boldsymbol{\alpha}$ is the center of f, $\boldsymbol{\beta}$ is the center of F, B is the initial radius of F, and R is the amount of isotropic hardening of F.

For the type of f, the anisotropic yield function by Hill in 1948 (Hill '48-type) was assumed.

The backstress $\alpha*$ expressing the relative kinematic motion of the center of f against the center of F is given by

$$\boldsymbol{\alpha}* = \boldsymbol{\alpha} - \boldsymbol{\beta} \tag{4}$$

The evolution equation of $\boldsymbol{\alpha}^*$, $\boldsymbol{\beta}$ and R is given by

$$d\boldsymbol{\alpha}* = C\left[\left(\frac{a}{Y}\right)(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - \sqrt{\frac{a}{\overline{\alpha*}}}\boldsymbol{\alpha}*\right]\overline{d\varepsilon^p} \tag{5}$$

$$\overline{\alpha*} = \sqrt{(3/2)\boldsymbol{\alpha}*:\boldsymbol{\alpha}*} \tag{6}$$

$$a = B + R - Y = (B - Y) + R = X_{sat} + R \tag{7}$$

$$d\boldsymbol{\beta} = m\left[\left(\frac{b}{Y}\right)(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - \boldsymbol{\beta}\right]\overline{d\varepsilon^p} \tag{8}$$

$$dR = m(R_{sat} - R)\overline{d\varepsilon^p} \tag{9}$$

where $\overline{d\varepsilon^p}$ is the equivalent plastic strain increment, C, b, R_{sat} and m are material constants. C has two values C_1 and C_2. The C_1 is used only the visitnity of the initial yielding, then it switches to $C = C_2$ in the subsequent deformation [2]. The material constants are determined so that calculation can express the experimental results of tensile-compressive test as shown in Table 2.

The Lankford value for SUS304 and SUS430 was also obtained as shown in Table 3 in order to represent the anisotropic property of the materials.

Table 2: Material constants of hardening model of Y-U model

Material	Y (MPa)	X_{sat} (MPa)	C_1	C_2	b (MPa)	R_{sat} (MPa)	m
SUS304	284	26	260	135	150	540	4
SUS430	300	50	260	280	60	230	10

Table 3: Lankford values

Material	0°	45°	90°
SUS304	0.989	1.089	0.932
SUS430	1.202	0.951	1.632

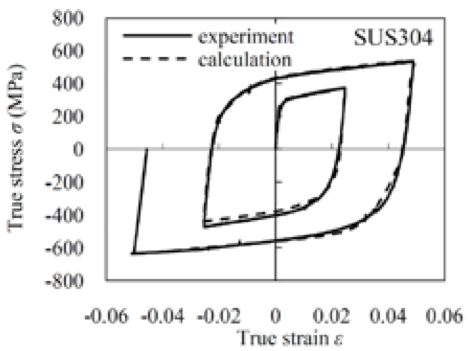

Figure 10. Comparison between experiment and analysis of SUS304 under tensile-compressive loading.

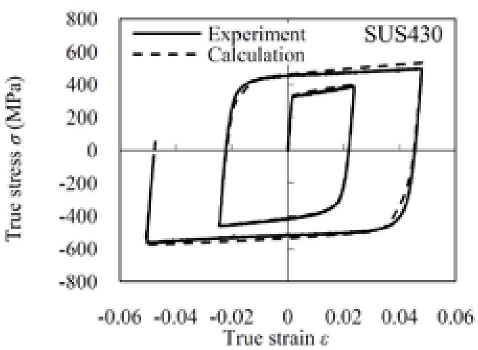

Figure 11. Comparison between experiment and analysis of SUS430 under tensile-compressive loading

Figures 10 and 11 show the comparison between experimental and calculated results of tensile-compressive loading using Y-U model with the material constants in Tables 2 and 3 of SUS304 and SUS430. The calculated results show good agreement with the experiments in both SUS304 and SUS430.

5 COMPARISON OF SPRINGBACK OF ACTUAL SHEET METAL PART WITH CALCULATION

Forming-springback analyses were performed by the part a using a finite element software ESI PAM-STAMP2G with the shell element. Forming process analysis was performed by stamping a blank sheet with a punch and a die by moving the die to the punch. The thickness of sheet metal is 1.5mm, Blank holder force (BHF) is 100kN, and Coulomb friction coefficient μ was set as 0.08.

Although the anisotropic characteristics on the change in Young's modulus was observed in stainless steel sheet from the experiments, equation (1) cannot express such anisotropy in single calculation. Therefore, in the present paper, three calculations were performed using material constants on the change in Young's modulus at 0°, 45° and 90°as shown in Table 1. The direction that springback of the part occur was at almost 90° from the RD, as the longitudinal direction of the part was along to RD. In the present case, therefore, the accuracy can be expected to be highest at the calculation by the material constants at 90°.

Prediction accuracy evaluation was performed by comparing the radius of curvature ρ_A and ρ_B of the calculated and the actual part formed at each section along the longitudinal direction in every 5 mm as shown in Figure 12. The 3-dimensional digital laser measurement system Konica-Minolta VIVID-9i was used for the measurement of the geometry of the actually formed part.

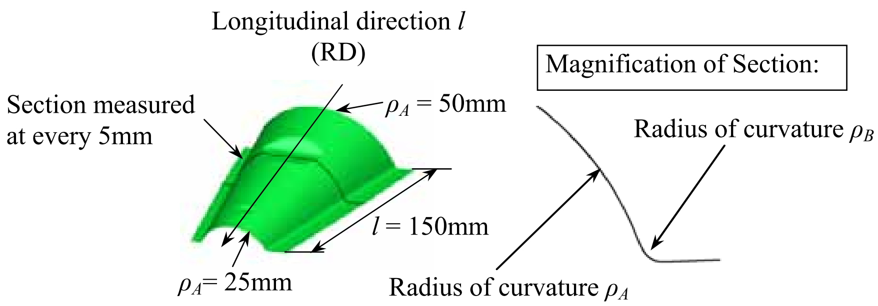

Figure 12. Shape of Part and Radius of curvature measured.

Figures 13 to 16 show the comparison of the values between calcualted and actual part in SUS304 and SUS430. The calculated result using the material constants of 90 from RD show the higher accuracy than the others. In the present case, the direction in which the springback occur is almost 90° from RD as expected. For SUS430 in Figures 15 and 16, the large difference can be observed. This is because the difference of the Young's modulus at 0 and 90 was significant as shown in Figure 8. From the results, the consideration of the anisotropic property of the change in Young's modulus was found out effective for more accu-rate prediction of the springback of the stainless steel sheet.

6 CONCLUSIONS

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The Y-U model was applied to stainless steel sheet SUS304 and SUS430 for more precise prediction of springback. From the tensile-compressive loading test for determination of the material constants of the Y-U model, the anisotropic property of plastic-deformation-dependent Young's modulus and the tendency was shown. Moreover, influence of consideration of the anisotropic property of the change in Young's modulus was investigated by com-paring calculated result with the actual part formed. The following results were obtained:

1. The anisotropic characteristics on Plastic-deformation-dependent Young's modulus were shown in SUS304 and SUS430. In SUS430, the dependence tendency at 45° is the same as the tendency at 90°, only the tendency at 0° is different. In SUS304 each tendency shows different tendency.
2. The consideration of the anisotropic property of the change in Young's modulus in the Y-U model was found out to be effective for more accurate prediction of the springback of the stainless steel sheet.

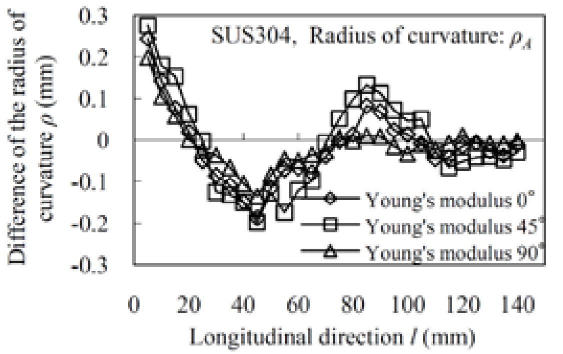

Figure 13: Difference of radius of curvature between experiment and analysis (SUS304, ρ_A)

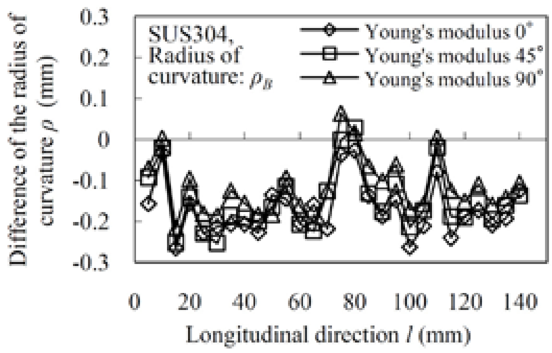

Figure 14: Difference of radius of curvature between experiment and analysis (SUS304, ρ_B)

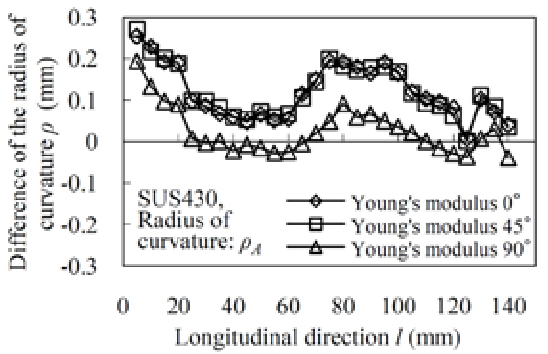

Figure 15: Difference of radius of curvature between experiment and analysis (SUS430, ρ_A)

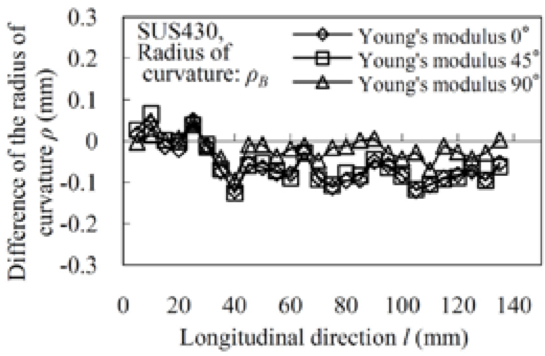

Figure 16: Difference of radius of curvature between experiment and analysis (SUS430, ρ_B)

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