Development New MAT Applied Yoshida 6th order Yield Function and its Verification

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1 Introduction

Sheet metal forming simulation has become an indispensable tool for design of automobile parts and process design of its die. As for automobile parts, high strength steel and aluminum alloy are applied for them in progress. On the other hand, these lightweight materials are well known as difficult formability, and many problems have occurred in stamping process.

In elasto-plastic FEA, there are many factors that determine the analysis accuracy, the material model is especially important. In case of applying associated flow rule, the yield function is key, and the reproductive capability of the material properties are very significant and influential. In LS-DYNA, there are many material models, and various yield function can be applied. MAT36(Barlet'89), MAT37(Hill'48), MAT242(Ylld2000-2D) [1] are commonly used in sheet metal forming. And this time, the MAT model that uses Yoshida 6th order yield function [2] are developed by using USER MATERIAL function in order to improve the accuracy. This MAT model take Yoshida-Uemori kinematic hardening model which is well known to be able to properly reproduce Bauschinger effect into account. And it can also strain dependency of Young's modulus into account. This yield function is applicable with 16 parameters both to shell elements as well as solid elements, therefore this model is user-friendly for users from this point of view. In addition, it is easy to consider anisotropic hardening which is important factor for accuracy. This model was implemented as MAT_289. In order to verify the analysis accuracy of this material model, the benchmarks of NUMISHEET 2018 [3] are calculated and the calculation results are compared with experimental data. Good results are also obtaine when shell elements are used and another case where application of solid elements are necessary. In this paper, the analysis results of MAT289 or the other MAT models are compared with experimental results.

2 The features of Yoshida 6th order yield function

Yoshida 6th order yield function is shown as follows.

$$
\begin{aligned}
f = {} & C_1\sigma_x^6 - 3C_2\sigma_x^5\sigma_y + 6C_3\sigma_x^4\sigma_y^2 - 7C_4\sigma_x^3\sigma_y^3 + 6C_5\sigma_x^2\sigma_y^4 - 3C_6\sigma_x\sigma_y^5 + C_7\sigma_y^6 \\
& +9\left(C_8\sigma_x^4 - 2C_9\sigma_x^3\sigma_y + 3C_{10}\sigma_x^2\sigma_y^2 - 2C_{11}\sigma_x\sigma_y^3 + C_{12}\sigma_y^4\right)\sigma_{xy}^2 \\
& +27\left(C_{13}\sigma_x^2 - C_{14}\sigma_x\sigma_y + C_{15}\sigma_y^2\right)\sigma_{xy}^4 + 27C_{16}\sigma_{xy}^4 = \bar{\sigma}^6 \qquad (1)
\end{aligned}
$$

There are 16 parameters in this equation, and in order to use them, their values need to be determined from the result of material tensile test. As the first feature of this function, it is possible to apply for shell elements and solid elements. Because it is assumed that out-of-plane deformation, which is a characteristic of sheet forming, has no effect on the accuracy. Another feature of this function is that it is relatively easy to expand it to anisotropic hardening. [4]

3 MAT models for sheet metal forming and patameter identification

Table 1 shows the major three MAT models that are corresponding with the anisotropic yield functions and they are ofen used for sheet metal forming analysis. They are MAT36 to which Barlet'89 can be applied, MAT242 to which Yld2000-2d can be applied, and MAT289 to which the Yoshida 6th-order function can be applied. For each MAT model, the number of parameters required for analysis is differenet, and it is necessary to determin from the material test results.

As the Yoshida 6th-order function needs as many as 16 parameters, the r value and YP value from uniaxial tensile tests at 0°, 225°, 45°, 67.5°, and 90° rolling direction as well as the results of biaxial tensile tests with three or more conditions are required.

	Number of parameter	Uniaxial tensile test		Biaxial tensile test
Barlet'89 (MAT 36)	3	3 tests are necessary (0°,45°,90°)	Lankford value or YP are necessary	Unnecessary
Yld2000-2d (MAT242)	8+1(Exponent parameter)	3 tests are necessary (0°,45°,90°)	Lankford value and YP are necessary	Equi-biaxial tensile test is necessary at least
Yoshida 6th order(MAT289)	16	5 tests are necessary (0°,22.5°,45°,67.5°,90°)	Lankford value and YP are necessary	Equi-biaxial tensile test and 2 more biaxial tensile test are necessary

Table 1: Parameter identification of each MAT model.

4 Apply to NUMISHEET2018 benchmark

4.1 Hole expansion in high-strength steel sheet

In order to investigate the influence on the analysis accuracy of each MAT model, the benchmark problem of NUMSIHEET2018 is solved. The Benchmark 1 posed at NUMISHEET 2018 was hole expansion in high-strength steel sheet. The 15 mm radius hole in the blank was expanded by the movement of the punch. The tool shape is shown in *Fig. 1*. The experiment results and simulation results of thickness strain value 2 mm from the edge of the material in the hole are compared.

The parameters of each yield function were determined from the experimental values from uniaxial tensile testing at 0.002 strain and 0.01 strain in the rolling direction and the experimental values from biaxial tensile testing regarding them as equi-plastic work. *Fig. 2* shows the r-value and normalized flow stress along the rolling angle. The caluculated value from all three yield functions match comparatively well with mechanical properties measured using uniaxial tensile tests. This is partly due to the fact that the Hill48 parameters were determined from the r-value. On the other hand, with regard flow stress, experimental values show a large divergence with the Hill48 yield function. Meanwhile the Yoshida 6th-order yield function and Yld2000-2d match the experimental values well.

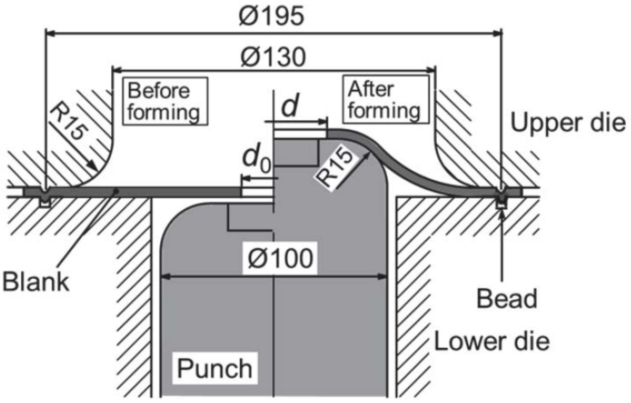
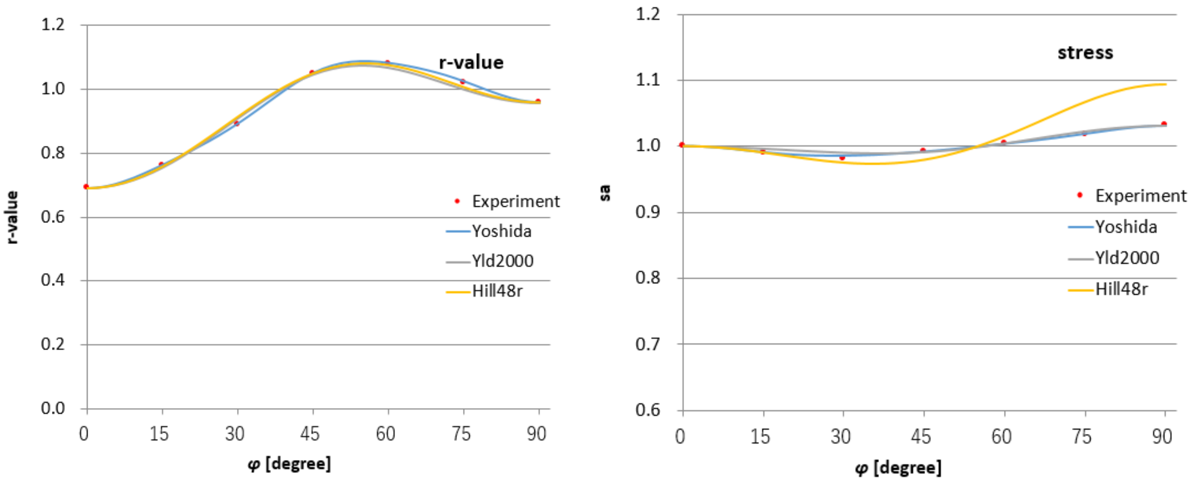


Fig. 1 Schematic illustration of the die geometry and specimen used for the hole expansion experiment. All dimensions are in millimeters.

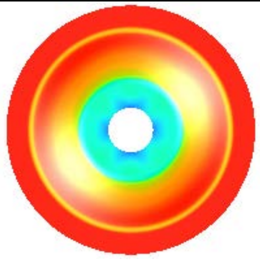
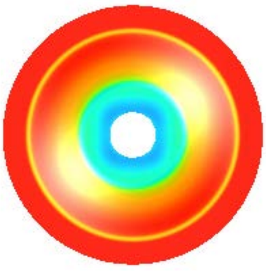
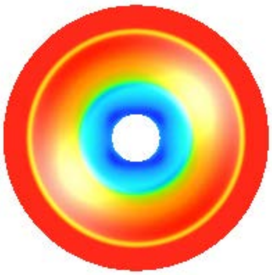


(a) (b)

Fig. 2 Mechanical properties measured using uniaxial tensile tests, with those calculated using Yoshida 6th order, Yld2000-2d and Hill'48 : (a) r-values, (b) flow stress at $\varepsilon_0^p = 0.01$ *.*

To validate the each MAT models, compare the analysis results with experimental resulrs. *Table 2* shows distribution of thickness strain from the calculation results at 1mm up from the dead point and the dead point. Analysis results from MAT289 and MAT242 are different especially around expanded hole. *Fig. 3* shows the result to compare the experimental values and analytical results for the sheet thickness strain along the expanded hole 2mm from the edge at punch stroke h=15mm. ***Fig. 3***(a) is obtained from MAT242 and MAT36. The analysis results of MAT242 are significantly shifted in the negative direction in comparison to the experimental results. It is thought that factors such as the friction coefficient may also influence the displacement of the range of values, but because the amplitude is gotton the greatest influence by the yield function, the analysis accuracy is not deemed to be very good. The phenomenon that weekly predicted maximum-minimum peaks of thickness strain distribution is also confirmed by other researcher. [5] And the analysis results of MAT36 have a larger amplitude but the phase is displaced.

Fig. 3(b) is obtained from MAT289. First of all, if the strain values on material tensile test used for parameter identification are different ($\varepsilon_0^p = 0.002$ and $\varepsilon_0^p = 0.01$), it is clear that the results differ even using the same MAT. When the strain is 0.002, the amplitude is small and the accuracy poor, but both the amplitude and phase match well in the 0.01 strain results. In other words, the result using strain 0.01 is closer to the experimetal values. The reason for this is that the strain at the measured and compared position is about 8%. From this, it is expected that analysis accuracy will be further improvement by considering anisotropic hardening.

	1mm up	Dead point
Yoshida 6th order $(\varepsilon_0^p = 0.01)$ MAT289		
Yld2000-2d $(\varepsilon_0^p = 0.01)$ MAT242		

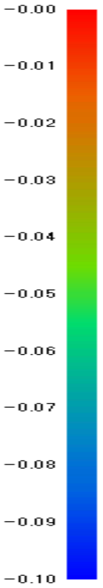


Table 2 Ditribution of thickness strain from MAT289 and MAT242 using $\varepsilon_0^p = 0.01$ *.*

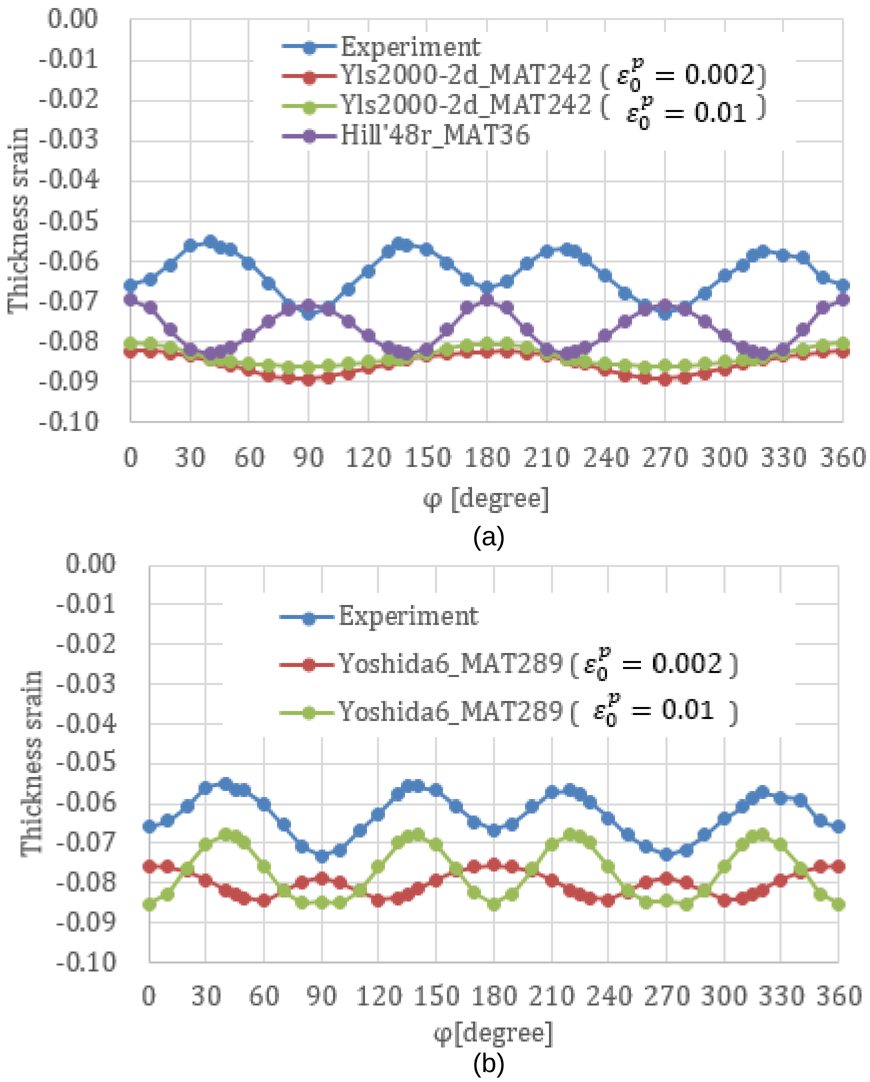


Fig. 3 Thickness strain along the expanded hole 2mm from the edge at punch stroke h=15mm : (a) MAT242 and MAT36 (b) MAT289

5 Summary

MAT289 that applies the Yoshida 6th-order yield function were developed by using USER MATERIAL function. MAT289 can not only apply the Yoshida 6th-order yield function but can also consider the Y-U model and Young's modulus strain dependence. MAT289 can be used with both shell elements and solid elements. On the other hand, various material tests have to be performed to extract the many parameters needed to use MAT289.

Then, to verify the application accuracy of MAT289, the benchmark problems from NUMISHEET 2018 were calculated by using several MAT models and compared them with experimental data. As a result, the problems using shell elements and problems using the solid elements were in good agreement with the experimental values, and high accuracy was achieved. Therefore, MAT289 is a material model useful for performing with high accuracy in sheet metal forming simulation.

6 Literature

[1] Barlet F,et al. , Plane stress yield function for aluminum alloy sheets – part1: theory, Int. J. Plast. 19, 2003, 1297-1319.
[2] Yoshida F,et al. , A user friendly 3D yield function to describe anisotropy of sheet steels, Int. J. Plast., 45, 2013, 119-139.
[3] http://numisheet2018.org/Benchmarks/index.html
[4] Yoshida F,et al. , Modeling of anisotropic hardening of sheet metals including description of the Baushinger effect, Int. J .Plast., 75, 2015, 170-188.
[5] Suzuki T. et al., Effect of anisotropy evolution on circular and oval hole expansion behavior of high-strength steel sheets, Int. J. Mech. Sci., 146-157, 2018, 556-570.