Simulations of plastic deformation by anisotropic hardening yield functions for QP1180

Zhe Chen and Yanshan Lou*
Xi’an Jiaotong University, Xi’an, 710049 Shaanxi, China

*ys.lou@xjtu.edu.cn

Abstract. This research compares the accuracy, computation efficiency and user-friendliness of the Hill48 and three anisotropic hardening models (S-Y 2009, CQN and newly proposed one) for QP1180 steel sheet. Experiments are conducted with dogbone and notched specimens along RD, DD and TD and bulging specimens for strain hardening behavior under equibiaxial tension. These models are calibrated by the experimental data above. The calibrated models are applied to simulate the uniaxial tension and plane strain tension tests for the metal. The simulation time and accuracy of the models are compared for both uniaxial tension and plane strain tension tests to evaluate their accuracy and computation efficiency. The results suggest that the CQN and proposed models are the most accurate among the four models compared, but the computation efficiency of the proposed model can dramatically reduce the numerical simulation time by 20%–40% compared to the CQN model. The comparison shows that the proposed model is the most accurate and is higher in numerical computation efficiency for engineers. Therefore, the proposed model is recommended to be utilized to describe anisotropic hardening behaviors during sheet metal forming processes.

1. Introduction

Accurate prediction of the plastic behaviour of textured sheet metals is of great importance for reliable numerical analysis of sheet metal forming. Numerous yield criteria are proposed to describe the plasticity of sheet metals [1-9]. These functions can provide accurate prediction of the yield surface of different materials. However, these yield functions are based on the assumption of isotropic hardening which assume that the yield surface shape does not change during plastic deformation. The function coefficients in these models are calibrated and determined in advance and will not change during numerical application. Experiments [10] show that hardening behaviors are different for different loading conditions and directions under proportional loading, which is referred to as anisotropic hardening. Various anisotropic hardening models [10-22] are proposed to more accurately describe the anisotropic hardening behaviour of metals by assuming that the yield surface changes during plastic deformation. The newly developed anisotropic hardening functions are more friendly to engineers since the inputs to numerical simulation are strain hardening curves at different loading conditions and directions instead of anisotropic parameters which are generally calibrated by an optimization code.

In this research, an anisotropic hardening model [21] is applied to describe the anisotropic hardening under uniaxial and plane strain tension for QP1180. Tensile tests are conducted with dogbone and notched specimens to characterize strain hardening behaviour under uniaxial and plane strain tension. Bulge tests are also conducted to acquire the equibiaxial tension data. Then the anisotropic hardening model is applied to simulate the experiments. The simulation result is compared with other isotropic hardening models and anisotropic hardening models to evaluate their performance.
2. Experiments

As illustrated in figure 1, three kinds of specimens with different shapes were tested to characterize plastic behaviour of QP1180 steel sheet including (a) dogbone specimen, (b) notched specimen and (c) bulge specimen. The material is 1.2 mm in thickness. Uniaxial tension tests were conducted with dogbone and notched specimens with the universal mechanical testing system. Deformation during experiments was measured by digital image correlation (DIC) as shown in figure 2. The bulge specimens are tested on the hydraulic bulge device with DIC recording as shown in figure 3.

To make sure that the experimental results are reliable, at least four of the dogbone and notched specimen were tested along the rolling direction (RD), diagonal direction (DD) and transverse direction (TD) for good repeatability. The yield stress is determined at 0.2% plastic strain and the hardening curves are described with the Swift-Voce hardening function as below:

\[
\sigma(\varepsilon_p) = \alpha K (\varepsilon_p + r_0)^n + (1 - \alpha) \left( A - (A-B) \exp(-C\varepsilon_p) \right)
\]

The material properties of QP1180 are then given in table 1. The force-stroke curves of dogbone and notched specimens are compared along different directions in figure 4, while the flow curves along different loading directions are compared in figure 5 (a). Figure 5 (b) shows the relative anisotropic strength with respect to plastic strain along different loading directions. Experimental results show that anisotropic hardening cannot be ignored for QP1180.
Table 1: Mechanical properties of QP1180 ($\sigma_y$: yield stress)

| stress state | $\sigma_y$ [MPa] | Strength [MPa] | Elongation [%] | $r$-value | $K$ [MPa] | $e_0$ | $n$ | A [MPa] | B [MPa] | C | $\alpha$ |
|--------------|------------------|----------------|---------------|----------|---------|-------|----|--------|--------|----|---------|
| RD           | 969              | 1215           | 20.4          | 0.750    | 2093.0  | 0.028 | 0.215 | 1531.8 | 973.7  | 11.04 | 0.5     |
| DD           | 956              | 1192           | 20.8          | 0.775    | 2057.7  | 0.028 | 0.216 | 1498.6 | 954.0  | 11.18 | 0.5     |
| TD           | 971              | 1209           | 17.8          | 0.698    | 2084.6  | 0.029 | 0.2156| 1511.3 | 980.1  | 11.48 | 0.5     |
| EB           | 1211             | NA             | NA            | 1        | 1769.0  | 0.0072| 0.1122| 1603.5 | 1077.9 | 8.71  | 0.5     |

Figure 3. Hydraulic bulge device and bulge Strain nephogram

Figure 4. Force-stroke curves of QP1180 for: (a) dogbone specimens; and (b) notched specimens

Figure 5. (a) Flow curves of QP1180 along different loading directions; (b) anisotropic evolution
3. Newly proposed anisotropic hardening function

The newly proposed anisotropic hardening model [21] is based on the S-Y 2009 [10] anisotropic hardening model, CQN model [12] and Cazacu’2018 function [7]. It is achieved by coupling the anisotropic hardening model S-Y 2009 and the Cazacu’2018 model. The S-Y 2009 part in this model can describe anisotropic hardening accurately while the Cazacu’2018 part can describe the yield surface for BCC and FCC materials. Besides, the new model is convenient to be applied in numerical simulation since it is in a form of stress invariants. Compared with the S-Y’2009 and CQN models, the new model can differentiate the plastic behaviour between BCC and FCC metals and is high in numerical computation efficiency. Its form is given under plane stress condition as:

\[
 f_e(\sigma, \bar{\lambda}) = b \left[ \left( \frac{\sigma_{11}}{\sigma_0(\lambda)} - \frac{\sigma_{22}}{\sigma_0(\lambda)} \right) \left( \sigma_{11} - \sigma_{22} \right) + \frac{\sigma_{11} \sigma_{22} - \sigma_{12} \sigma_{21}}{\sigma_0^2(\lambda)} + 4 \sigma_{12} \sigma_{21} \right] \left( J_2^{\frac{1}{3}} - c J_2 \right) \]

\[
 b = \left( \frac{729}{27 - 4c} \right)^{\frac{1}{3}}
\]

\( \bar{\lambda} \) is the plastic compliance. The parameter \( c \) is 1.5776 for BCC metals and 2.5116 for FCC metals. Besides, by restricting the parameter \( c \) within the range of \([-27/5, 3]\), the yield surface is guaranteed to be convex. It also should be mentioned that the newly proposed model can be extended to spatial stress condition as described by Chen et al. [21].

4. Application of the new model to QP1180

The material properties of QP1180 are characterized by the newly proposed model in Eq. (2) to describe the anisotropic hardening. Figure 6 illustrates the comparison of experimental hardening curves and the theoretical prediction of the new model of QP1180. It can be observed that the predicted hardening curves along RD, DD, TD and EB are identical with experimental results. It is quite natural because these four hardening curves are the input parameters of the new model. Therefore, it can be concluded that the new model can accurately describe the anisotropic hardening along RD, DD, TD and EB directions.

Figure 6. Comparison of true stress-true strain curves under uniaxial tension (RD, DD and TD) and equibiaxial tension between experiments and prediction for QP1180
To provide a more intuitive description of the anisotropic hardening of the material and the performance of the anisotropic hardening models, the evolution of the yield surface predicted by Hill48, S-Y 2009, CQN and the new model and the experimental results are given in figure 7. Obviously, the isotropic hardening Hill48 model can only describe initial yield surface. The prediction error of the Hill48 function increases as the plastic strain increases. For the three anisotropic hardening models, their description remains accurate as the plastic strain increases. It is also noted that the shape of the S-Y 2009 yield surface is larger than the other two yield surfaces around plane strain. Theoretically, it is the advantage of the CQN and proposed models since the Hill48-based S-Y 2009 model describes higher strength under plane strain than experimental result of BCC and FCC metals.

![Figure 7. Yield surface evolution prediction compared with experimental results](image)

To evaluate the performance of the proposed model, numerical simulations were carried out with ABAQUS/Explicit with solid elements (C3D8R) for uniaxial tension test of dogbone and notched specimen along RD, DD and TD. The force-stroke curves are extracted and calculated from simulation and are compared with experimental results. Figure 8 illustrates the force-stroke curves of dogbone specimens along RD, DD and TD between experiments and numerical simulation. For the load-stroke prediction, it is obvious that all the yield functions can precisely predict the experimental results along RD. All the three anisotropic hardening models can predict the reaction forces along DD and TD with very high accuracy, but the Hill48 function predicts the force-stroke curves along DD and TD with poor accuracy. It is quite natural because the flow curves along these three directions are the input parameters for the three anisotropic hardening models, but the isotropic hardening Hill48 function only takes the flow curve along RD into account during simulation.

The prediction error of the load-stroke curves is compared in figure 9 for the dogbone specimens. It is apparent that the maximum prediction error is less than 2% for the load-stroke curves of dogbone specimens along three directions for all the three anisotropic hardening models. The comparison shows that all the three anisotropic hardening models are capable of modelling different strain hardening behaviors along three loading directions with high accuracy. The isotropic hardening Hill48 function predicts satisfactory experimental results along RD, but the error exceeds 5% for the dogbone specimens along DD and TD, which indicates the limitation of Hill48 for anisotropic hardening characterization.
Figure 8. Comparison of force-stroke curves of dogbone specimens between experiments and simulation for QP1180: (a) RD; (b) DD; and (c) TD.
Figure 9. Prediction error of flow curves of the dogbone specimens: (a) RD; (b) DD; and (c) TD

Figure 10 illustrates the force-stroke curves of the notched specimens along RD, DD and TD between experiments and numerical simulation. It is obvious that the Hill48 function over-predicts the reaction forces along all the three directions, especially along DD and TD. The prediction accuracy is highly improved by the three anisotropic hardening models. Among the three anisotropic hardening functions, the S-Y 2009 model slightly over-estimates the reaction force along the three directions and the trend is very similar with the experimental results. The CQN and newly proposed models predict the results with higher accuracy than the Hill48 and S-Y 2009 functions.

Figure 10. Comparison of force-stroke curves of notched specimens between experiments and simulation: (a) RD; (b) DD; and (c) TD
The prediction error of the load-stroke curves is compared in figure 11 for the notched specimens. It is apparent that the error of the Hill48 function is higher than 5%, which is not acceptable. For the S-Y 2009 model, the maximum error exceeds 3% along RD. For the CQN and proposed models, the error is within 2%. Therefore, the CQN and proposed models provide the best prediction accuracy for the notched specimens along the three directions.

From the accuracy evaluation above, the Hill48 function is the worst in accuracy, the CQN and the proposed models are the best and the S-Y 2009 function is inbetween. Therefore, these functions are further evaluated by comparison of the numerical computation cost. The computation time are listed in table 2 for the notched specimen along TD of these four constitutive models. It is observed that the Hill48 function is the most efficient in numerical computation because of its simplicity. It takes about 40% longer for the Hill48-based S-Y 2009 function compared with the Hill48 function. The CQN model needs the longest time to run the simulation, which is about 3.0 times longer for the notched specimen compared with the Hill48 function. For the proposed model, it takes shorter time to finish the simulation for notched specimens compared to the CQN model, with 48% increase in numerical computation efficiency.

Table 2: Simulation time of notched specimens for QP1180 (unit: s)

| specimen   | Hill48 | S-Y 2009 | CQN  | proposed |
|------------|--------|----------|------|----------|
| Notched TD | 201    | 284      | 595  | 307      |

5. Conclusions

This research characterizes the anisotropic hardening behaviour of QP1180 steel sheet by a newly proposed anisotropic hardening model as well as the Hill48, S-Y 2009 and CQN models. The
comparison with experimental results shows that the CQN and new models are the best in predicting accuracy. Further evaluation of computation costs shows that the new model can reduce about 48% of computation time compared with the CQN model. Therefore, the proposed anisotropic hardening model is suggested to characterize the anisotropic behaviour of sheet metal due to its advantages in high accuracy, low computation cost and user-friendliness.

Acknowledgments
The authors would like to acknowledge the financial supports by the National Natural Science Foundation of China (52075423 and U2141214)

References
[1] Hill R 1948 Proc. Roy. Soc. London Ser. A 193 281
[2] Barlat F and Lian K 1989 Int. J. Plasticity 5 51
[3] Barlat F, Lege DJ and Brem JC 1991 Int. J. Plasticity 7 693
[4] Barlat F, Brem JC, Yoon JW, Chung K, Dick RE, Lege DJ, Pourboghrat F, Choi S-H and Chu E 2003 Int. J. Plasticity 19 1297
[5] Lou Y, Huh H and Yoon JW 2013 Int. J. Mech. Sci. 66 214
[6] Yoon JW, Lou Y, Yoon J and Glazoff MV 2014 Int. J. Plasticity 56 184-202
[7] Cazacu O 2018 Int. J. Solids Struct. 139 200
[8] Lou Y and Yoon JW 2018 Int. J. Plasticity 101 125
[9] Lou Y, Zhang S and Yoon JW 2019 Int. J. Mech. Sci. 161 105027
[10] Stoughton TB and Yoon JW 2009 Int. J. Plasticity 25 1777
[11] Cai Z, Diao K, Wu X and Wan M 2016 Int. J. Mech. Sci. 107 43
[12] Lee EH, Stoughton TB and Yoon JW 2017 Int. J. Plasticity 99 120
[13] Li H, Hu X, Yang H and Li L 2016 Int. J. Plasticity 82 127
[14] Li H, Zhang HQ, Yang H, Fu MW and Yang H 2017 Int. J. Plasticity 90, 177
[15] Park N, Stoughton TB and Yoon JW, 2019 Int. J. Plasticity 121 76
[16] Hou Y, Min J, Stoughton TB, Lin J, Carsley JE and Carlson BE 2020 Int. J. Plasticity 135, 102808
[17] Hu Q, Yoon JW, Manopulo N and Hora P 2021 Int. J. Plasticity 136, 102882
[18] Hu Q and Yoon JW 2021 Int. J. Plasticity 140, 102978
[19] Hu Q, Yoon JW and Stoughton TB 2021 Int. J. Mech. Sci. 201, 106467
[20] Hu Q and Yoon JW 2022 Int. J. Plasticity 151, 103214
[21] Chen Z, Wang Y and Yoon JW 2022 Mech. Mater. 165, 104190
[22] Hu Q, Chen J and Yoon JW 2022 Mech. Mater. 167, 104245