Strain hardening under large deformation for AA5182

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Abstract. In this study, an aluminium alloy of AA5182 is taken as the research object to study strain hardening under large plastic deformation. Tensile tests are done for four specimens, including dog-bone specimens, notched specimens, specimens with a central hole and in-plane shear specimens. Bulging tests are also conducted to measure strain hardening under balanced biaxial tension. In addition, an experimental method called in-plane torsion test is also used for shear loading. At least three experiments are completed for each type of specimens along the rolling direction (RD), diagonal direction (TD), and transverse direction (DD). The stroke of each tests is measured by a digital image correlation (DIC) system, and the load-stoke curves were obtained for the tests. Combined with an inverse engineering method, the strain hardening properties are calibrated for the alloy under different loading conditions of shear, uniaxial tension, plane strain tension, and balanced biaxial tension. The strain hardening under various loading conditions is compared and modelled by various yield functions to evaluate their performance. It is concluded that inverse engineering approach is a simple but powerful method to obtain the stress-strain curve up to large plastic deformation. It is also observed that it needs to develop yield functions to model yielding behaviour under complex loading conditions.

1. Introduction
Numerical simulation is now widely used in the design of sheet metal forming processes. The material models implemented in simulation need to be identified to describe the plastic behaviour of sheet metals. Accurate description of strain hardening properties is one of typical tasks for the identification of material models. The conventional method to obtain the strain hardening properties is by conducting a standard uniaxial tensile test with the standardized testing procedure and specimen geometry. However, the standard tensile test can usually only reach the equivalent plastic strains of 0.2 to 0.3 before the necking begins for good ductile metals. The large deformation conditions must be considered to meet industrial production requirements. In the last decade, the inverse method to determine the hardening properties has been widely used [1-15] to determine the hardening properties by incorporating the simulation with experimental data (e.g. global load-stroke curve, local strain fields, etc.). It is critical to apply the reliable material models in simulation.

In this study, several specimens are tested to consider the multiple loading conditions under large plastic deformation, including shear, uniaxial tension, plane strain tension, and balanced biaxial tension. In addition, an experiment called in-plane torsion test is also introduced and specimens are designed according to [16, 17]. The stress-strain curve is calculated analytically for standardized specimens while...
strain hardening for other specimens are obtained by inverse engineering method. Combining with an inverse engineering method, the strain hardening properties were calibrated under various loading conditions and modelled by a Drucker yield function to evaluate its performance.

2. Experiments
As illustrated in Figure 1, six kinds of specimens with different shapes, including dog-bone specimens I, specimens with central hole II, notched specimens III, in-plane shear specimens IV, bulging test specimens with a die opening diameter of 160mm and in-plane torsion shear specimens, were tested to obtain the strain hardening properties under various loading conditions. Specimens I-IV are tested on an electronic universal tensile testing machine of INSTRON 5182. In addition, Figure 1 also shows the initial gauge lengths for stroke measuring by digital image correlation (DIC) of I-IV specimens. The in-plane torsion shear specimens were tested on the in-plane torsion test device developed in Xi’an Jiaotong University.

At least three experiments were conducted for specimens I-IV along the rolling direction (RD), diagonal direction (DD), and transverse direction (TD), as shown in Figure 2 with good repeatability. Solid pentagrams for specimens II-IV indicate the experimental onset of ductile fracture. For specimens with a central hole II, force drops very early along RD compared with those along TD and DD. However, fracture is not observed at load drop along RD and the mechanism is not clear currently. To determine the material anisotropy quantitatively, the r-values and 0.2% proof stress are computed as 0.527 and 169.8Mpa for RD, 0.557 and 166.6 Mpa for DD, 0.537 and 171.0Mpa for TD, respectively. Accordingly, the metal is assumed isotropic. For in-plane torsion shear specimens VI, the DIC measurement method is applied to calculate the torsion angle denoted as $\theta_{dic}$.

3. Analytical calculation of stress-strain curves
For dog-bone specimens, bulging test specimens and in-plane torsion shear specimens, the hardening properties of the materials can be obtained through theoretical calculation.

By processing the load-stroke curves data in Figure 2(a), the true stress-strain curves are represented in Figure 3 with black line and it can be seen that the strain is about 0.23 before the necking occurs. The Swift, Voce and Swift-Voce models are fitted by the experimental true stress-strain curve calculated from the uniaxial tensile tests and hardening under large deformation is predicted as well in Figure 3.

Hardening under shear is computed analytically by the in-plane torsion test according to Figure 4 (a) and [16-17]. The computed stress-strain curve in shear is compared with strain hardening measured in by uniaxial tension in Figure 4 (b). It is observed that there is big difference between these two stress states. The equivalent strain value is obtained by the DIC as shown in Figure 4 (c). The strain distribution on the shear zone is not uniform, so the equivalent strain of shear zone along the transverse direction was averaged at each torsion angle. The averaged strain is combined with calculated stress to get hardening behaviour in shear from the in-plane torsion test.

![Figure 1. Six types of specimens: (I) dog-bone; (II) with central hole; (III) notched; (IV) in-plane shear; (V) bulging test; (VI) in-plane torsion](image-url)
Figure 2. The load-stroke curves along three direction: (a) dog-bone specimens; (b) specimens with central hole; (c) notched specimens; (d) in-plane shear specimens

Figure 3. Stress-strain curves calibrated by Swift, Voce, and Swift-Voce laws for dog-bone specimen

Figure 4. In-plane torsion shear test: (a) analytical computation of hardening in shear; (b) comparison of hardening between shear and uniaxial tension; (c) DIC strain distribution of shear zone
4. Inverse engineering approach for strain hardening characterization

The strain hardening properties of the material is also closely related to the choice of the yield function. Two yield functions were chosen to study the effect of yield functions on strain hardening properties. One is the commonly used von Mises yield criterion, and the other is Drucker yield function [17] which considers the effect of third invariant on yielding. The Drucker yield function is shown as below:

\[ \sigma_{ij} = a \left( J^2 - cf_j^2 \right)^{1/6} \]  

(1)

According to Lou and Huh [18-20], Eq. (1) can be formulated in terms of Lode parameter \( L \) and von Mises equivalent stress \( \bar{\sigma}_{VM} \) in a form of

\[ \sigma_{ij} = a \left( \frac{1}{27} - c \frac{4L^2(L^2-9)}{729(L^2+3)^2} \right)^{1/6} \bar{\sigma}_{VM} \]  

(2)

AA5182 belongs to an aluminum alloy which is a typical FCC material. According to [18], the material constant \( c \) in the Drucker yield function is advised 2.0 for FCC materials and \( a = 1.8365 \).

The strain hardening in the numerical simulation is described by the Swift-Voce law as below:

\[ \sigma_{ij} = K (e_0 + \varepsilon^p)^n (A - (A - B) \exp(-C e^p)) \]  

(3)

where \( K, e_0, n, A, B \) and \( C \) are the parameters to describe the hardening properties of AA5182.

Numerical simulations were carried out in ABAQUS/Explicit using VUMAT with solid elements (C3D8R) for tensile test specimens II-III, and in-plane torsion shear specimen VI. Load-stroke curves are extracted from numerical simulations. The numerical results are compared with experimental measurement to calibrate hardening parameters in Eq. (3) for each tests. The optimization of hardening parameters and numerical simulation are automatically conducted by a developed in-house script [15]. The “Downhill Simplex” algorithm is utilized, which is one of the search methods that can handle nonlinear problems. Initial hardening variables are obtained from the results of dog-bone specimens. The hardening parameters are optimized when the error of each specimens \( err_m \) below is minimized.

\[ err_m = \sqrt[\sum n=1]{\left( \frac{F_{num} - F_{exp}}{F_{ave}} \right)^2} \]  

(4)

where \( n \) is the number of samples, \( F_{num} \) and \( F_{exp} \) is the simulated and experimental values corresponding to the \( i \) sample, \( F_{ave} \) is the average of force values in the experimental load-stroke curves.

5. Results and discussion

The optimized stress-strain curves obtained by the Drucker yield function for each specimen are shown in Figure 5(a). The maximum strain of curves is up to the strain before fracture. It can be seen that one hardening curve can describe the hardening of the loading states for three specimens under the Drucker yield function because the stress-strain curves of specimens with central hole II, notched specimens III, and in-plane torsion shear specimens VI approximately coincide with each other except for the bulging test. But there is big difference for the strain hardening curves optimized by inverse engineering approach with the von Mises yield function as shown in Figure 5(b), which indicates that the von Mises function cannot describe yielding under different stress states.

The comparison in Figure 5(a) also shows that the inverse engineering approach is very proper to get strain hardening under large plastic deformation compared with the analytical calculation for the dog-bone specimen. For dog-bone specimens, the hardening can be analytically calculated up to about 0.23 for the alloy, while with the inverse engineering approach, the stress hardening can be Obtained at a strain to 0.45 for notched specimen, 0.49 for specimen with a central hole and 0.5 for the in-plane torsion test. The analytical calculation by the bulging test can also provide hardening curve up to large strain of about 0.6. It indicates that the in-plane torsion test combined with inverse engineering approach is approximately equivalent with the bulging test in term of providing strain hardening information under large strain.
6. Conclusions
Six different tests are conducted to investigate the strain hardening behaviour under large deformation for AA5182. Analytical calculation and inverse engineering approach are used to calibrate strain hardening behaviour under large strain. The results show that the Drucker function provides much better prediction of yielding and hardening under different stress states. The inverse engineering approach is very powerful to get the strain hardening properties under large strain. Its comparison with the bulging test proves that the inverse engineering approach and the bulging test are approximately equivalent in term of largest strain up to which the hardening properties can be obtained.

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References
[1] Joun, M., Eom, J.G., Lee, M.C., 2008. A new method for acquiring true stress–strain curves over a large range of strains using a tensile test and finite element method. Mech. Mater. 40 (7), 586–593.
[2] Kamaya, M., Kawakubo, M., 2011. A procedure for determining the true stress–strain curve over a large range of strains using digital image correlation and finite element analysis. Mech. Mater. 43, 243–253.
[3] Kim, J.H., Serpantié, A., Barlat, F., Pierron, F., Lee, M.G., 2013. Characterization of the post-necking strain hardening behavior using the virtual fields method. Int. J. Solids Struct. 50 (24), 3829–3842.
[4] Tardif, N., Kyriakides, S., 2012. Determination of anisotropy and material hardening for aluminum sheet metal. Int. J. Solids Struct. 49 (25), 3496–3506.
[5] Nasser, A., Yadav, A., Pathak, P., Altan, T., 2010. Determination of the flow stress of five AHSS sheet materials (DP 600, DP 780, DP 780-CR, DP 780-HY and TRIP 780) using the uniaxial tensile and the biaxial viscous pressure bulge (VPB) tests. J. Mater. Process. Technol. 210 (3), 429–436.
[6] Knysh, P., Korkolis, Y.P., 2017. Identification of the post-necking hardening response of rate- and temperature-dependent metals. Int. J. Solids Struct. 115–116, 149–160.
[7] Lou, Y., Huh, H., 2013. Prediction of ductile fracture for advanced high strength steel with a new criterion: experiments and simulation. J. Mater. Process. Technol. 213, 1284–1302.
[8] Peirs, J., Verleysen, P., Van Paepegem, W., Degrieck, J., 2011. Determining the stress–strain behaviour at large strains from high strain rate tensile and shear experiments. Int. J. Impact Eng. 38, 406–415.

[9] Zhao, K., Wang, L., Chang, Y., Yan, J., 2016. Identification of post-necking stress–strain curve for sheet metals by inverse method. Mech. Mater. 92, 107–118.

[10] H. Zhang, S. Coppieters, C. Jiménez-Peña, D., 2019. Debruyne, Inverse identification of the post-necking work hardening behaviour of thick HSS through full-field strain measurements during diffuse necking, Mech. Mater. 129, 361-374.

[11] Rossi, M., Lattanzi, A., Barlat, F., 2018. A general linear method to evaluate the hardening behaviour of metals at large strain with full-field measurements. Strain 54.

[12] Denys, K., Coppieters, S., Debruyne, D., 2018. On the identification of a high-resolution multi-linear post-necking strain hardening model. CR. Mecanique 346, 712–723.

[13] Lou, Y., Chen, L., Clausmeyer, T., Tekkaya, A.E., Yoon, J.W., 2017. Modeling of ductile fracture from shear to balanced biaxial tension for sheet metals. Int. J. Solids Struct. 112, 169-184.

[14] Brosius, A. , Yin, Q. , A. Güner, & Tekkaya, A. E., 2011. A new shear test for sheet metal characterization. Steel Research International, 82(4), 323-328.

[15] Lou, Y., Zhang, S.J., Yoon, J.W., 2020. Strength modeling of sheet metals from shear to plane strain tension. Int. J. Plast. 102813. https://doi.org/10.1016/j.ijplas.2020.102813.

[16] Yin, Q. , Soyarslan, C. , A. Güner, Brosius, A. , & Tekkaya, A. E., 2012. A cyclic twin bridge shear test for the identification of kinematic hardening parameters. International Journal of Mechanical Sciences, 59(1), 31-43.

[17] Drucker, D.C., 1949. Relations of experiments to mathematical theories of plasticity. J. Appl. Mech. 16, 349–357.

[18] Lou, Y., Yoon, J.W., 2018. Anisotropic yield function based on stress invariants for BCC and FCC metals and its extension to ductile fracture criterion. Int. J. Plast. 101, 125–155.

[19] Lou, Y., Huh, H., 2013. Extension of a shear controlled ductile fracture model considering the stress triaxiality and the Lode parameter. Int. J. Solids Struct. 50, 447-455.

[20] Lou, Y., Yoon, J.W., Huh, H., 2014. Modeling of shear ductile fracture considering a changeable cut-off value for the stress triaxiality. Int. J. Plast. 54, 56–80.