Stress-Strain Characterization for Reversed Loading Path and Constitutive Modeling for AHSS Springback Predictions

Hong Zhu, Mai Huang, Sriram Sadagopan and Hong Yao
ArcelorMittal Global R & D - East Chicago, 3001 E. Columbus Drive, East Chicago, IN 46312, USA
hong.zhu@arcelormittal.com

Abstract. With increasing vehicle fuel economy standards, automotive OEMs are widely using various AHSS grades including DP, TRIP, CP and 3rd Gen AHSS to reduce vehicle weight due to their good combination of strength and formability. As one of enabling technologies for AHSS application, the requirement for requiring accurate prediction of springback for cold stamped AHSS parts stimulated a large number of investigations in the past decade with reversed loading path at large strains followed by constitutive modeling. With a spectrum of complex loading histories occurring in production stamping processes, there were many challenges in this field including issues of test data reliability, loading path representability, constitutive model robustness and non-unique constitutive parameter identification. In this paper, various testing approaches and constitutive modeling will be reviewed briefly and a systematic methodology from stress-strain characterization, constitutive model parameter identification for material card generation will be presented in order to support automotive OEM’s need on virtual stamping. This systematic methodology features a tension-compression test at large strain with robust anti-buckling device with concurrent friction force correction, properly selected loading paths to represent material behavior during different springback modes as well as the 10-parameter Yoshida model with knowledge-based parameter-identification through nonlinear optimization. Validation cases for lab AHSS parts will also be discussed to check applicability of this methodology.

1. Introduction
In order to meet stringent needs on both strength and formability / ductility to ensure lighter weight vehicle design with strong safety performances, a spectrum of AHSS grades with different microstructures has been developed from DP with ferrite and martensite (shown in Figure 1) to 3rd Gen AHSS with more complex microstructure: ferrite, bainite, retained austenite and martensite (shown in Figure 2) by properly selecting alloying contents and controlling thermal-mechanical processes. With increased strength accompanied by reducing thickness in designing cold stamped parts, roadblocks for FEA simulation-assisted springback control still exist and are more difficult to pass in the field of stress-strain characterization for reversed loading paths and constitutive modeling.

ArcelorMittal Global R & D – East Chicago has been dedicating to developing and applying advanced plasticity testing with constitutive modeling to characterize our newly developed AHSS grades and generate FEA material cards for our automotive customers. A methodology developed recently in our lab for testing existing and emerging AHSS grades will be summarized in this paper.
2. Selection for testing system with anti-buckling fixture for large strain

To model bending-unbending associated sheet behavior when the blank flows into the die cavity or passes through drawbeads, stress-strain behaviors under reversed loading at large strain must be properly characterized for springback prediction. Several testing approaches including direct bending-unbending test, reversed pure-shearing test, and tension-compression test are developed in past two decades and some of them are discussed by Lemoine et al (Lemoine, 2011) on their advantages and limitations. With the structure nature of various bending-unbending tests, constitutive models have to use to inverse model parameters through complex optimization procedure. Comparing with reversed shearing test, tension-compression test is more popular since it can be performed on the conversional testing frame and data can be directly synchronized with standard tensile test (i.e., ASTM) results without knowing material yielding behavior as precondition.

Among existing anti-buckling fixture system developed in past decade, three promising systems were selected for further evaluation using 1.0 mm DP980 to test their robustness and applicable domains (Boger, 2005; Knoerr, 2014; Dietrich, 2014). After conducting evaluative testing, it was decided to adopt a similar testing fixture as suggested by Dietrich (Dietrich, 2014).

3. Representative loading paths

Typical springback modes include angle opening from unbending, and side wall curl caused by bending-unbending, three-dimensional twisting from inhomogeneous wall curl and bowing from global unbending (Zhu, 2010). Following Hill’s last recommendation for further development of plasticity (Hill, 1994), stress-strain behaviors of representative loading paths during these modes should be characterized and incorporated in the constitutive modeling to model stress properly.

Two loading paths have been chosen to characterize stress-strain behaviors using this newly developed testing system for reversed loading at large strain. The strain history of path 1 is from 0% to 5% to 0% to 20% (or fracture) to represent bending-unbending-stretching occurred on side-wall. It is possible to reach 30% plastic strain in this loading path with 20% on tension mode. The strain history of path 2 is designed from 0% to 5% to 0% to -5% to 0% to represent sheet’s behavior through drawbead. Two or three-cycle loading path (Shi, 2008; Knoerr, 2014) is not considered here due to difficulties of monitoring buckling and straighten during these cycles and less significance on representing realistic behavior in stamping processes. Depending on AHSS grade’s uniform deformation, pre-strain magnitudes for the above two loading paths can be extended to 10%, which is the limit of extensometer for this system.
In Figure 3 and Figure 4, engineering stress-strain curves from these two loading paths are shown for a 1.5 mm DP980T700Y grade with three duplicated tests along rolling direction. Good repeatability for these two loading paths are observed to prove the testing system robustness and small variation of associated material behavior for this grade.

Figure 3. Eng. stress-strain curves from path 1  Figure 4. Eng. stress-strain curves from path 2

4. Advanced plasticity model and parameter identification

Conventional plasticity theory is used to describe metal stress-strain behavior under simple loading path with permanent (plastic) deformation through a curve of the effective-plastic-strain and stress, yield surface and flow rule. When loading path reverses, various complex phenomena including Bauschinger effect and transient effect are observed (Yoshida, 2004), which originate from dislocation evolutions and internal stress among different microstructures from different length scales (Bate, 1986; Haddadi, 2006). These phenomena are common for all steels grades but are more severe for AHSS due to stress and / or strain partitioning in their multi-phase microstructures such as ferrite, martensite, bainite and retained austenite with different strength.

Hu et al (Hu, 1992) developed a physical-based phenomenological model using four internal variables to represent complex microstructure evolution such as the directional strength, polarity and rearrangement of the dislocation substructures for mild steel. Considering that only limited knowledge under complex loading paths for multi-phase microstructure of AHSS has been developed, it is not feasible to develop fully physical-based material models to capture the observed phenomena at current stage.

Several phenomenological models have been developed to capture the observed phenomena in reversed loading path tests. Among them, Armstrong and Frederick (Armstrong, 1966) proposed a nonlinear kinematic hardening model for back stress evolution to model the reversal loading test. Chaboche (Chaboche, 1983) generalized this-type of models with multiple back stress evolutions. Over last fewer years, Yoshida’s two-surface model (Yoshida, 2002; Yoshida, 2003) has become more and more popular for AHSS springback prediction in recent years due to its good nature to balance model’s complexity and robustness.

In Yoshida’s model, yield surface’s evolution is through movement of the center controlled by one back stress while the size of yield surface kept constant, bounding surface’s evolution has both center moving described by other back stress and the size expansion. Two enhancements have been made and implemented in LSDYNA from its initial version (Yoshida, 2002): Shi et al (Shi, 2008) used Swift-type equation to replace Voce-type equation in the initial version for the expansion of the bounding surface to suppress the non-physical saturation of stress-strain behavior generated from the model; material card 125 in the latest version of LSDYNA (LSTC, 2015) restored C1 and C2 parameters in the model to describe the difference on initial hardening behavior before and after reversed loading. We selected this 10-parameter Yoshida model based on two modifications mentioned above to calibrate and generate the material cards for our customers.
Stress-strain curves from several represent loading paths are used to calibrate this 10-parameter Yoshida model or stiff differential equation system through a nonlinear optimization technique. The calibrated parameters are associated with the initial parameter setting and not unique. MatPara (CEM, 2012) developed by Prof. Yoshida is selected for calibrating parameters due to its special strength-dependent initial parameter setting based on extensive knowledge build in the past decade.

Three material cards for model 125 in LSDYNA for 1.5 mm DP980T700Y are generated from different combinations of loading paths and initial setting to calibrate. 1st one is from two loading paths: loading path 1 and loading path 2 with initial setting from 980 MPa default in MatPara; 2nd one from three loading paths: loading path 1, loading path 2 and full range of stress-strain curve in uniaxial tensile test (Huang, 2009) with initial optimized setting from two loading paths; 3rd one from three loading paths: loading path 1, loading path 2 and full range of stress-strain curve in uniaxial tensile test (Huang, 2009) with initial setting from 980 MPa default in MatPara. Predicated stress-strain behaviors from the calibrated 10-parameter Yoshida model are compared with the experimental results respectively in Figure 5 to 7. As seen in the figures, with increase number of the loading path, the optimization become more challenging.

Fig. 5. Experiments and model from 2 paths

Fig. 6. Experiments and model from 3 paths with the optimized initial
5. Lab validations

Channel-type parts for this 1.5 mm DP980T700Y grade were stamped using a servo-mechanical press (AIDA 2000) for three forming modes: bending only, bending-unbending (without draw-bead) and bending-reversed-bending (with draw-bead), as shown in Figure 8. These stamped parts were scanned by an ATOS system shown in Figure 9 for comparing with the FEA predicted shapes based on different calibrated constitutive models.

FEA models were built and FEA simulations for forming and springback were performed based on LSDYNA R7.1.2 with revision 95028 released on 01/07/2015. The results from the isotropic hardening (material model 37 in LSDYNA) and 10-parameter Yoshida model (model 125 in LSDYNA) calibrated by different loading paths, were compared.

As shown in Figure 10, for bending only forming mode, using Yoshida’s model can slightly improve the springback simulation accuracy comparing with the isotropic model. For bending-unbending mode shown in Figure 11 as well as bending-reversed-bending shown in Figure 12, Using Yoshida’s model can significantly improve the springback simulation accuracy comparing with the
isotropic model. The predicted results from the material card calibrated from two loading paths and the material card calibrated from three loading paths with the optimized initial setting are very close.

Fig.10. Stamped vs. predicted parts: bending Fig.11. Stamped vs. predicted parts: bending unbending

Fig.12. Stamped vs. predicted: bending-reverse-bending Fig.13. Different calibrations: bending-reverse-bending

As discussed in the section of the parameter identification, the calibrated Yoshida parameters from the different initial setting will be different. This difference on model’s parameter also has influence on the final springback prediction as shown in Figure 13.

This study has been extended to a spectrum of AHSS steel grades with the strength from 590 MPa to 1300 MPa. It is found that the conclusions are similar as this 1.5 mm DP980T700Y.

6. Conclusions / Summary
A systematic methodology from stress-strain characterization through tension-compression-tension tests at large strain, constitutive model parameter identification for material card generation has been developed. This methodology has been validated for different springback modes for a spectrum of AHSS grades from 590 MPa to 1300 MPa for a channel draw part.

References
[1] A reference Armstrong, P.J., Frederick, C.O., 1966. A mathematical representation of the multiaxial bauschinger effect. CEGB report, RD/B/N731, Berkeley Nuclear Laboratories.
[2] Bate, P.S., Wilson, D.V., 1986. Analysis of the Bauschinger effect, Acta Metall. 34, 1097-1105.
[3] Boger, R.K., Wagoner, R.H., Barlat, F., Lee, M.G., Chung, K., 2005. Continuous, large strain, tension / compression testing of sheet metal. Int. J. of Plasticity 21, 2319-2343.
[4] Cao, J., Lee, W., Cheng, H.S., Seniw M., Wang, H., Chung, K., 2009. Experimental and numerical investigation of combined isotropic-kinematic hardening behavior of sheet metals. Int. J. of Plasticity 25, 942-972.
[5] CEM Institute, 2012. MatPara Manual V 2.0.0.
[6] Chaboche, JL, Rousselier, G., 1983. On the plastic and viscoelastic constitutive equations. Part I and part II. Transactions of ASME, Journal of Pressure Vessel Technology 105, 153-164.
[7] Dietrich, L., Socha, G. and Kowalewski, Z.L., 2014. Anti-buckling fixture for large deformation tension-compression cyclic loading of thin metal sheets. Strain – An
International Journal for experimental mechanics, volume 50, issue 2, pp 174-183.

[8] Hill, R., 1994. Classical plasticity: a retrospective view and a new proposal. Journal of the Mechanics and Physics of Solids, 42, No. 11, 1803-1816.

[9] Haddadi, H., Bouvier, S., Banu, M., Maier, C., Teodosiu, C., 2006. Towards an accurate description of the anisotropic behavior of sheet metals under large plastic deformations: modeling, numerical analysis and identification. International Journal of Plasticity 22, 2226-2271.

[10] Hu, Z., Rauch, E.F., Teodosiu, C., 1992. Work-hardening behavior of mild steel under stress reversal at finite strains. International Journal of Plasticity 8, 839-856.

[11] Huang, G., Zhu, H., Yan, B., 2009. A novel approach for generating full range stress strain using digital image correlation and finite element analysis. SAE Technical Paper 2009-01-0470.

[12] Knoerr, L., Sever, N., and Faath, T., 2014. Cyclic tension compression testing of AHSS flat specimens with digital image correlation system. NUMISHEET 2014 conference proceeding, Melbourne, Australia.

[13] Lemoine, X., Durrenberger, L., Zhu, H., Kergen, R., 2011. Mixed hardening models: parameters identification on AHSS steels. 2011 IDDRG Conference, Bilbao, Spain.

[14] LSTC, 2015. LS-DYNA keyword user’s manual (R8.0), Volume II, Materials models 125, 03/18/15 (r: 6307).

[15] Shi, M., X. Zhu, C. Xia, T.B. Stoughton, 2008. Determination of nonlinear isotropic / kinematic hardening constitutive parameters for AHSS using tension and compression tests, NUMISHEET 2008, Interlaken, Switzerland.

[16] Yoshida, F., Uemori, T., 2002. A model of large-strain cyclic plasticity describing the Bauschinger effect and work hardening stagnation. International Journal of Mechanical Plasticity 18, 661-686.

[17] Yoshida, F., Uemori, T., 2003. A model of large-strain cyclic plasticity and its application to springback simulation. International Journal of Mechanical Sciences 45, 1687-1702.

[18] Zhu, H., Huang, L., Wong, C., 2004. Unloading modulus on springback in steels. SAE Technical Paper 2004-01-1050.

[19] Zhu, H., Sriram, S., Yan, B., Duroux, P., 2010. Advanced material characterizations and constitutive modeling for AHSS springback predictions. SAE Technical Paper 2010-01-0980

ACKNOWLEDGMENTS

The authors wish to thank ArcelorMittal for the permission to publish this paper.

Thanks also go to Prof. Z.L. Kowalewski at Poland Institute of Fundamental Technological Research, Prof. R. H. Wagoner and Dr. John Chen at Ohio State Univ., Dr. L. Knoerr and Dr. N. Sever (former ArcelorMittal), Dr. C. Du. at FCA, Prof. F. Yoshida at Hiroshima Univ., Dr. L. Zhang at LSTC for helping on establishing this comprehensive methodology. G. Girman and G. Volk at ArcelorMittal are always appreciated for conducting complicated and tedious tests. Dr. P. Venkatasurya at ArcelorMittal for sharing 3rd Gen AHSS microstructure.