Identification Protocol of Yoshida-Uemori Hardening Model

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Abstract. The Yoshida-Uemori model is a combined hardening model coupled with the elastic modulus evolution which depends on the equivalent plastic strain. A lot of publications show that it allows to improve the springback prediction compared to a classical isotropic hardening model. It is implemented in the most used FEA stamping codes (Autoform®, Ls-Dyna® and Pamstamp®) with some variations and it is more and more used in automotive industry. ArcelorMittal decided to provide material cards to its customers. To achieve this goal, ArcelorMittal has at one’s disposal the equipment to perform reverse shear tests and hysteresis loops for all steel grades. An in-house methodology has been developed to identify the Yoshida-Uemori adjusting parameters in a very precise and robust manner. The material cards are produced for each FEA stamping code, considering the specificities of the implementations.

1. Introduction

A lot of authors recommend the use of combined hardening models to improve prediction of the springback [1-5]. The combined hardening Yoshida-Uemori model [6-8] is implemented in the most used FEA stamping codes (Autoform®, Pamstamp® and LS-Dyna®) with occasionally some variations [9, 10]. This model describes the specificities of stress-strain response to cyclic hardening (Figure 1):

- The plastic strain dependence of the elastic modulus.
- The Bauschinger effect characterized by early re-yielding strength, transient effect and work-hardening stagnation. The work-hardening stagnation appears later when the Ultimate Tensile Strength increases, and the length of the plateau increases with the pre-strain level.
- The permanent softening, characterized by a stress offset observed after the transient stage, which increases with the pre-strain level.
Figure 1. Description of the different stages of Bauschinger effect on a Stress-strain curve in tension-compression [8]

2. Yoshida-Uemori models

2.1. Combined hardening model.
The Yoshida-Uemori hardening model, presented originally in 2002 [6-8], involves three different surfaces in the plane-stress space. A pure kinematic hardening model is imposed for the Yield surface with a combined hardening model for the Bounding surface. As the evolutions of Yield and Bounding surfaces are not enough to model permanent softening and work-hardening stagnation, an additional surface has been introduced. In 2008, Shi et al. [9] suggested to replace the Voce law by Swift law to improve the prediction of formability. In 2015, Yoshida et al. [10] added the possibility to use a linear combination between Swift and Voce isotropic hardening laws.

2.2. Elastic modulus evolution model.
The Yoshida-Uemori combined hardening model is coupled with a non-linear elastic modulus model. The evolution of the elastic modulus is a function of the plastic pre-strain level (equation (1)).

\[ \varepsilon(p) = E_0 - (E_0 - E_a)(1 - \exp(-\xi p)) \]

where \( E_0 \) is initial Young modulus; \( E_a \) and \( \xi \) are two material parameters, \( p \) is equivalent plastic strain.

3. ArcelorMittal experimental tests needed for the identification of material parameters

3.1. Reverse shear tests needed for the identification of combined hardening model
Many reverse experimental tests (tension-compression, compression-tension, reverse shear or bending-unbending tests) allow to evaluate the material combined hardening by imposing a displacement in one direction and then imposing another displacement in the opposite direction. The advantages and disadvantages of each reverse test are detailed in [12].

We advise the reverse shear test for several reasons. First because there is no limitation due to diffuse necking like in compression-tension or tension-compression tests (Figure 2). Next, the buckling limit of very thin sheets is observed later compared to a compression loading. Last, very large plastic deformation (0.3–0.5 in equivalent plastic strain) and pre-strain levels can be reached, which are representative of strain levels in stamping. And finally, our reserve shear equipment allows to determine the behavior of all steel grades from 250 to 2000 MPa and from 0.5 to 4 mm sheet thickness.
A shear test is performed by imposing a displacement on a piston, while maintaining constant the gap between grip wedges. Since the area of interest in the simple shear specimen is very small, a high-resolution optical technique must be used to determine the shear plastic strain $\gamma$ in the middle area of the specimen. This approach is a reliable way to avoid boundary effects creating normal stresses at the vicinity of specimen corners. To ensure accurate measurements, it is not recommended to consider pre-strain levels below 0.04.

The identification tools are programmed with tension-compression data inputs. Then, it is necessary to generate an equivalence between tension-compression and the shear flow curve (red curve on figure 3). A coefficient $\chi$ is determined by an inverse method to match the equivalent shear curve (green curve) with the uniaxial tensile curve (blue curve).

**Figure 2.** Comparison flow curves for a reverse shear test (SH +/-) (orange curves) vs compression-tension test (C-T) (black curves) for DP600 [12]

**Figure 3.** Equivalent tension-compression stress-strain determination.

3.2. Hysteresis loop used for the identification of elastic modulus evolution model

The adjusting parameters governing the evolution of the elastic modulus are identified thanks to hysteresis loops conducted between 0.2% of plastic deformation and uniform elongation (Uel) every 1% on ISO 12.5x50 uniaxial tensile specimens (Figure 4a). The strain is measured with a high-resolution Zwick® digiClip extensometer as per Annex G of ISO 6892-1 standard. For each unloading/reloading loop, the elastic modulus is considered as the slope crossing points A (maximal stress at the begin of the loop) and B (minimal stress of loop) (figure 4b). The slope is deducted from the linear regression on unloading path between the points A and B.
Figure 4. Determination of the pre-strain dependence of the elastic modulus for DP780 a) Hysteresis loop (orange curve) conducted every 1% until the end of the uniform elongation b) the elastic modulus is the slope deducted from the linear regression (blue curve) on unloading path (black curve) between points A and B.

4. Methodology to produce material cards according Yoshida-Uemori model for ArcelorMittal steel grades

The identification of adjusting parameters governing the evolution of the elastic modulus is treated separately from the identification of combined hardening parameters defined in Yoshida-Uemori model.

4.1. Identification of the evolution of the elastic modulus

The two adjusting parameters $E_a$ and $\xi$ are fitted according to a gradient method (red curve on figure 5) in order to get the better correspondence between equation (1) and experimental results derived from hysteresis loops tests (blue points).

Figure 5. Experimental points (blue dots) versus Elastic modulus evolution model (red line) for a DP780 steel ($E_0 = 200GPa, E_a = 152GPa$ and $\xi = 50.03$)

4.2. Identification of combined hardening parameters defined in Yoshida-Uemori model

We have developed an in-house methodology to identify Yoshida-Uemori material parameters, so that the model fits at best: 1) the experimental curves (one uniaxial tensile load and three uniaxial compressive loads are considered at the same time), 2) the following mechanical characteristics of the uniaxial tensile test: Yield Stress (YS), Ultimate Tensile Strength (UTS), Uniform Elongation (UEL%) and hardening coefficient ($n$).
The central component of the methodology is the direct solving of Yoshida-Uemori equations for the case of uniaxial loads. Then, fitting of the experimental curves and mechanical characteristics are performed by optimization techniques available in LS-OPT [13] using an inverse approach.

When compared to MatPara® software developed by Prof. Yoshida for the identification of the Yoshida-Uemori material parameters, the present methodology considers: 1) several experimental curves at the same time, 2) all the combined hardening parameters at the same time (especially parameters for Swift and Voce laws and the mixing coefficient between these two laws all together).

4.2.1. Direct solving of the equations for the case of uniaxial loads
The solving of the Yoshida-Uemori model equations for the “one dimension” case has been developed to calculate the model variables (α, β, R and σ – see table 1) for a given set of material parameters (Y, B, C1, C2, m, Rsat, b, K, ε0, n, μ – see table 1).

| Equations |
|-----------|
| \( R_{\text{voce}}(p) = R_{\text{sat}}[1 - \exp(-mp)] \) (2) |
| \( R_{\text{swift}}(p) = K\{(\varepsilon_0 + p)^n - \varepsilon_0^n\} \) (3) |
| \( R(p) = \mu R_{\text{swift}}(p) + (1 - \mu)R_{\text{voce}}(p) \) (4) |
| \( \dot{\theta}(p) = C[a - \sqrt{a(b(p))}]p \) with \( a = B + R - Y \) (5) |
| where \( C = C_1 \) when Max(\( \theta(p) \)) < B - Y and \( C = C_2 \) otherwise (6) |
| \( \dot{\theta}(p) = mp(b - \beta(p))p \) (7) |
| \( \alpha(p) = \theta(p) + \beta(p) \) (8) |
| \( Y^2 = [\sigma(p) - \alpha(p)]^2 \) (9) |

| Variables |
|-----------|
| α(p)[MPa] Translation of the Yield Surface (blue cross in figure 6) |
| β(p)[MPa] Translation of the Bounding surface (orange circle in figure 6) |
| R(p)[MPa] Expansion of the Bounding surface (red square in figure 6) |
| σ(p)[MPa] True stress (large black dot in figure 6) |

| Parameters |
|-----------|
| Y [MPa] Initial size of Yield surface |
| B [MPa] Initial size of Bounding surface |
| C1 [MPa] Rate of translation of the Yield surface, with respect to the centre of the Bounding surface, until plastic strain is below a threshold value calculated in the model using parameters Y and B |
| C2 [MPa] Rate of translation of the Yield surface, with respect to the center of the Bounding surface when the threshold value of plastic strain has been exceeded (\( C_1 > C_2 \)) |
| EPREF Additional parameter in PamStamp. The equation (6) of the Yoshida-Uemori model allows to calculate the threshold value of plastic strain to switch from \( C_1 \) to \( C_2 \). But ESI asks the user to choose a value of plastic strain for the threshold value to switch from \( C_1 \) to \( C_2 \), called EPREF in the PamStamp material card |
| m Parameter of Voce law (used for expansion of the Bounding surface) and rate of translation of the Bounding surface |
| \( R_{\text{sat}} \) [MPa] Saturated value for expansion of the Bounding surface, parameter of Voce law |
| b [MPa] Saturated amount of translation of the Bounding surface |
| K [MPa] Parameter for Swift hardening law (used for expansion of the Bounding surface) |
| \( \varepsilon_0 \) Parameter for Swift hardening law (used for expansion of the Bounding surface) |
\( n \) Parameter for Swift hardening law (used for expansion of the Bounding surface)

\( \mu \) Mixing factor between Swift and Voce (combined laws for expansion of the Bounding surface)

The solving time is very quick. Results are illustrated at two states; at the end of a tensile load in figures 6.a and during a compressive load in figures 6.b. In both cases, the position of the Yield surface, Bounding surface and symbols for the model variables \( \alpha, \beta, R, \) and \( \sigma \) are illustrated (left figures) with the corresponding evolution of those variables (right figures).

\[ \text{Figure 6. Yoshida-Uemori combined hardening model at two states: a) end of a tensile load and b) during a compressive load.} \]

Note that the two parameters of the Yoshida-Uemori model for work hardening stagnation (\( h \) and \( r_0 \)) have not been included in the solving for two reasons. First, the work hardening stagnation is negligible for AHSS steels. Second, there are some discrepancies in the work hardening stagnation implementation: a) between MatPara and PamStamp® (different results when \( r_0=0 \)), b) between MatPara and LS-DYNA® (\( r_0 \) is not required in this stamping software). The ways of implementation of work hardening stagnation in these two FEA codes must be clarified with the support of the stamping editors before introducing these two work-hardening stagnation parameters in material cards.

At the opposite, the direct solving includes the parameter EPREF, which is required in the PamStamp® material card. In PamStamp®, it is the threshold value of plastic strain to switch from \( C_1 \) to \( C_2 \). Direct solving can be performed for two options: a) calculation of EPREF being the value of \( p \) for
which \(\text{Max}(\theta(p))\) exceeds \(B-Y\) for the first time (according equation (6) in table 1), b) the threshold value \(\text{EPREF}\) is chosen by the user as an input value and equation (6) is replaced by \(C=C_1\) when \(p<\text{EPREF}\), \(C=C_2\) otherwise.

The direct solving results have been validated for several sets of material parameters: same results as with MatPara software and as with LS-Dyna® and Pamstamp® simulations of tensile-compressive uniaxial loads.

4.2.2. Inverse approach developed to fit the experimental curves and the mechanical characteristics of tensile test

An inverse approach has been developed with LS-OPT software which proposes a lot of optimization methods and algorithms for material parameters identification.

A multi-objective function to be minimized has been defined, which includes 8 objectives. Four objectives deal with the tensile test material properties (\(Y_S, UTS, UEL\%\) and \(n\)): the calculated material properties must be as close as possible to experimental values. Four other objectives deal with the minimization of gaps between the four experimental and predicted stress-strain curves.

Several optimization technics available in LS-OPT (Genetic Algorithm, Adaptive Simulated Annealing, …) and several metamodels (Polynomial, Radial Basis Function Network, Feedforward Neural Network, …) have been tested. The “Adaptive Simulated Annealing” (ASA) optimization algorithm and the “quadratic polynomial” metamodel were selected, as the most suitable for this problem. At each optimization process iteration, direct solving approach is performed for several hundred sets of Yoshida-Uemori material parameters from a DOE (design of experiences) defined by LS-OPT. The metamodel is calculated and the optimization algorithm is run. The design space (minimum and maximum values for the material parameters) of the DOE is automatically updated at each iteration using the “Sequential with Domain Reduction” (SRSM) strategy.

The proposed methodology allows to create material cards for PamStamp® and LS-DYNA® stamping softwares. For Autoform®, the parameters of the simplified kinematic hardening model developed by Autoform (called « AKH » model) [2,3,11] are identified directly from experimental tensile-compressive curves. It is possible to input parameters of Yoshida-Uemori model since version R8 of Autoform®, but the model is not really implemented. It is automatically converted and replaced by the « AKH » model for the FEA simulations. We don’t recommend to input the parameters of Yoshida-Uemori model found with our methodology in Autoform®.

5. Very accurate results of our methodology

Two applications are presented for DP780 and Fortiform®1180 steel grades. Very good fitting of experimental curves (figure 7) and tensile test material properties (table 2) are found.

\[\text{Figure 7. Identification results for a) DP780 and for b) Fortiform®1180 steel grades.}\]
Table 2. Tensile test material properties of DP780 and for Fortiform®1180 steel grades.

|                  | YS [MPa] | UTS [MPa] | UEL [%] | Hardening coefficient n |
|------------------|----------|-----------|---------|-------------------------|
| DP780 - Experimental | 495      | 815       | 12.7    | 0.148                   |
| DP780 - Fitted    | 495      | 816       | 12.7    | 0.144                   |
| Fortiform®1180 - Experimental | 976      | 1197      | 9.7     | 0.118                   |
| Fortiform®1180 - Fitted | 971      | 1199      | 9.7     | 0.113                   |

There is not a unique solution for the Yoshida-Uemori material parameters. But prediction of springback for an industrial part is very weakly modified by the choice of the solution. We have checked this for 7 industrial parts whose springback has been calculated for 2 solutions that fit both very well the experimental data (table 3). The differences of springback prediction for 6 out of 7 parts are negligible: the cost and the delay for the management of springback in the stamping tools and process setup are the same for the 2 solutions.

Table 3. Comparison of springback prediction for 7 parts with the 2 solutions

| Material parameter (PamStamp® name) | Gap between the 2 solutions | Springback prediction for 7 parts | Maximal gap on the part between the 2 solutions |
|-------------------------------------|-----------------------------|----------------------------------|-------------------------------------------------|
| B-Y (XSATI)                         | 10%                         | Roof arch reinforcement          | 0.3 mm                                          |
| b (BSAT)                            | ~0%                         | Siderail part                    | 1.8 mm                                          |
| m (AM)                              | ~0%                         | Side sill closing part           | 0.7 mm                                          |
| C1 (CX1)                            | 20%                         | Door lateral beam                | 1.1 mm                                          |
| C2 (CX2)                            | ~0%                         | Rear siderail part               | 1 mm                                            |
| ε0 (YOSHIDA-EPSILON0)               | 100%                        | Upper A-pillar reinforcement part | 0.2 mm                                          |
| K (YOSHIDA-K)                       | 20%                         | Floor reinforcement part         | 0.3 mm                                          |
| n (YOSHIDA-N)                       | 20%                         |                                  |                                                 |

The development of the proposed methodology has allowed to get a very good knowledge of the various implementations of Yoshida-Uemori model in the stamping softwares.

First example: results of our direct solving for the ‘one dimension’ case and exchanges with ESI technical support have helped to confirm recommendations for the values of some material parameters in PamStamp®, and to clarify the user’s documentation of this stamping software.

Second example: the writing of the correspondence table between the material parameters of Yoshida-Uemori model for PamStamp® and for LS-DYNA®. This table allows an easy conversion of a LS-DYNA® material card ‘125’ in a PamStamp® material card. Also, this table shows the conditions to make possible the conversion of a PamStamp® material card in LS-DYNA® material card and the cases when this conversion is not possible.

6. Conclusions and prospects

By using the Yoshida-Uemori model in FEA stamping softwares, a better prediction of springback is observed. Then geometrical conformity of stamped parts is got quicker and at a lower cost at our customers.

ArcelorMittal decided to provide its customers with material cards according this model. To achieve this goal, we have at our disposal the equipment to perform reverse shear tests and hysteresis loops for all our steel grades. In 2021, we have developed our own methodology to fit in a very precise manner both the experimental tension-compression curves (equivalent to reverse shear curves) and the mechanical characteristics of tensile test. The central component of the methodology is the direct solving of the equations of Yoshida-Uemori model for the case of uniaxial loads. Fitting is performed by using optimization techniques.

ArcelorMittal is now ready to produce accurate Yoshida-Uemori material cards for its products, considering the various implementations of this model in the most used stamping softwares PamStamp®, LS-DYNA® and Autoform®.
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