Key Engineering Materials Vols. 554-557 (2013) pp 1245-1251
© (2013) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/KEM.554-557.1245

A Plasticity Induced Anisotropic Damage Model for Sheet Forming Processes

M. S. Niazi[1, a], V. T. Meinders[2, b], H. H. Wisselink[1, c], C. H. L. J. ten Horn[3, d], G. Klaseboer[4, e] and A. H. van den Boogaard[2, f]

[1]Materials innovation institute, P.O. Box. 5008, 2600 GA Delft, The Netherlands

[2]Faculty of Engg. Tech., University of Twente, 7500 AE Enschede, The Netherlands

[3]Tata Steel RD&T, P.O. Box 10000, 1970 CA IJmuiden, The Netherlands

[4]Philips Consumer Lifestyle, Process Engineering, Forming, P.O. Box 201, 9200 AE Drachten, The Netherlands

[a]M.Niazi@m2i.nl, [b]V.T.Meinders@utwente.nl, [c]H.Wisselink@m2i.nl, [d]Carel.ten-Horn@tatasteel.com, [e]Gerrit.Klaseboer@philips.com, [f]A.H.vandenBoogaard@utwente.nl

Keywords: Load Induced Anisotropic Damage, Material Induced Anisotropic Damage, Viscoplastic Regularization; Dual Phase Steel, Failure, Sheet Metal Forming

Abstract. Plastic deformation induces damage in Advanced High Strength Steels (AHSS). Therefore damage development in these steels shall be studied and incorporated in the simulations for accurate failure predictions in forming processes and for determination of the product properties after forming. An efficient anisotropic damage model suitable for large scale metal forming applications has been developed. The standard Lemaitre anisotropic damage model was modified to incorporate lower damage evolution under compression, strain rate dependency in damage and Material Induced Anisotropic Damage (MIAD). Viscoplastic regularization proved to be effective in removing the pathological mesh dependence of the presented local damage model. Anisotropic damage development was characterized in Dual Phase (DP600) steel. The damage model parameters for DP600 were determined from experiments. The Modified Lemaitre's (ML) anisotropic damage model was validated with experiments.

Introduction

Plastic deformation induces damage in Dual Phase (DP) steels and other Advanced High Strength Steels (AHSS). Damage in a material usually refers to the presence of micro defects in the material. During damage evolution, micro defects initiate, grow and interact with each other. The microstructure of DP steels has martensitic phase islands (grains) embedded in a soft ferritic matrix. When the material is plastically deformed, the different deformation behavior of these phases gives rise to voids and cracks within the martensite phase or at the interfaces of both phases. Therefore, damage material models should be used for failure prediction and to determine the forming limit curve (FLC) for these advanced materials.

Most researchers take damage to be isotropic. However, this assumption limits the applicability of the model and can produce inaccurate (in some cases misleading) results. For correct and accurate results, damage shall be considered as anisotropic. Anisotropy in damage can be categorized based on the cause which induces the anisotropy; the loading state or the material microstructure. According to the Load Induced Anisotropic Damage (LIAD) model, damage will be higher in one direction (compared to the other two orthogonal directions) if the material is deformed more in this direction, irrespective of the microstructure of the material. According to the Material Induced Anisotropic Damage (MIAD) model, the material will have different damage characteristics for different orientations in the sheet if there is an anisotropy in shape or distribution of the particles responsible for damage (hard second phase particles, inclusions or impurities).

The article at hand presents an efficient anisotropic damage model to simulate complex failure mechanisms and accurately predict failure in advanced materials and processes. First the standard Lemaitre's anisotropic damage model [1] is modified for damage development under compression state and influence of strain rate on damage. Viscoplastic regularization is used to avoid pathological mesh dependency. The MIAD phenomenon in DP600 is experimentally characterized using tensile tests in combination with optical strain measurement system (ARAMIS) and Scanning Electron Microscopy (SEM). Then the model is modified to account for MIAD. This modified version of Lemaitre's anisotropic damage model i.e. ML anisotropic damage model is validated with cylindrical cup deep drawing tests. In this article, only the MIAD validation of the model is discussed, for the validation of the LIAD part, therefore referred to [2,3].

Load Induced Anisotropic Damage

Lemaitre's anisotropic damage model [1] was used as a starting point. This model was modified to account for lower damage evolution under compression and strain rate dependency in damage.
Standard Lemaitre's damage model. Thermodynamics is the basic ingredient of a continuum damage model. The Gibbs specific free enthalpy Ψ^* for Lemaitre's damage model is given by:

$$\Psi^* = \Psi_{\mathrm{e}}^* + \frac{1}{\rho}\sigma_{ij}\varepsilon_{ij}^{\mathrm{p}} - \Psi_{\mathrm{p}} - \Psi_{\mathrm{T}} \tag{1}$$

Where Ψ^* and Ψ_e^* are the Legendre transformation of the total Helmholtz free energy and the elastic part of the Helmholtz free energy, respectively, Ψ_{p} and Ψ_{T} are the plastic hardening and thermal contribution to the Helmholtz free energy, respectively.

Several assumptions are made to simplify the implementation of the model. The process is assumed to be isothermal ($\Psi_{\mathrm{T}} = 0$), a small strain formulation with an additive split of the strain tensor is taken, elasticity is assumed to be isotropic and only isotropic hardening will be considered. The elastic potential, based on the hypothesis of strain equivalence for anisotropic damage, is defined by Lemaitre [1]:

$$\Psi_e^* = \frac{1}{\rho}\left[\frac{1+\nu}{2E} H_{ij}\sigma_{jk}^{dev} H_{kl}\sigma_{li}^{dev} + \frac{3(1-2\nu)}{2E}\frac{\left(\sigma^H\right)^2}{1-\eta D^H}\right] \tag{2}$$

where η is the hydrostatic sensitivity parameter, D^{H} is hydrostatic damage derived from the second order damage tensor **D** and **H** is the second order damage effect tensor defined as a function of **D**

$$H = (I_2 - D)^{-\frac{1}{2}} \tag{3}$$

The state law for the evolution of elastic strain tensor $\boldsymbol{\varepsilon}^{\mathrm{e}}$ (observable state variable) is given by:

$$\varepsilon_{ij}^e = \rho\frac{\partial \Psi_e^*}{\partial \sigma_{ij}} = \frac{1+\nu}{E} H_{ik}\sigma_{kl}^{dev} H_{lj} + \frac{1-2\nu}{E}\frac{\sigma^H}{1-\eta D^H}\delta_{ij} \tag{4}$$

The dissipation potential F_{D}, for anisotropic damage, proposed by Lemaitre [1] is given by:

$$F_D = \left(\frac{\bar{Y}}{S}\right)^s Y_{ij}\left|\frac{d\varepsilon^p}{dr}\right|_{ij} \tag{5}$$

Where $|..|$ applied to a tensor means the absolute value in terms of the principal components. $\bar{Y}$ is the effective damage energy release rate, r is the isotropic hardening variable whereas S and s are material parameters. The second order damage tensor **D** is defined as an internal state variable with the second order damage energy release rate **Y** as the associated state variable. The evolution law for the damage tensor is defined by using the normality rule and Equation (5)

$$\dot{D} = \left(\frac{\bar{Y}}{S}\right)^{s} |\dot{\varepsilon}^{p}| \tag{6}$$

Equation (6) is valid when the damage threshold is reached i.e. $\varepsilon_{\mathrm{eq}}^{\mathrm{p}} > \varepsilon_{\mathrm{D}}^{\mathrm{p}}$. The failure (initiation of a mesocrack) is assumed to occur when $\mathrm{D}_{I} \geq D_{\mathrm{c}}$. Where $\varepsilon_{\mathrm{eq}}^{\mathrm{p}}$ is the equivalent plastic strain, $\varepsilon_{\mathrm{D}}^{\mathrm{p}}$ is the damage threshold, D_{I} is the maximum principal damage component and D_{c} is the critical damage value. The effective energy release rate $\bar{Y}$ depends upon the effective stress (undamaged material). The mapping function from the nominal stress to effective stress is given by Lemaitre [1] as follows:

$$\widetilde{\boldsymbol{\sigma}} = \left(\mathbf{H} \cdot \boldsymbol{\sigma}^{\mathrm{dev}} \cdot \mathbf{H}\right)^{\mathrm{dev}} + \frac{\sigma^{\mathrm{H}}}{1-\eta D^{\mathrm{H}}} \mathbf{I}_{2} \tag{7}$$

The mapping function defined in Equation (7), not only defines a different influence of damage on the hydrostatic and deviatoric part of the stress but also gives a symmetric effective stress tensor. The formulation given in Equations (1) to (7) fulfills the requirement of second law of thermodynamics for all allowed cases $(0 \leq \mathrm{D}_{I} \leq 1)$ [2].

Modifications. In metals, damage is mainly due to voids. Voids have negligible growth under significant negative hydrostatic stresses. Only nucleation of voids can occur under negative triaxiality. Therefore the difference of damage evolution for metals under tension and compression needs to be incorporated in the Lemaitre's anisotropic damage model. The material parameter S in Equations (5) and (6) is modified to S_{c} such that $S_{\mathrm{c}} = S \cdot u_{\mathrm{f}}$. The parameter u_{f} is defined as a function of triaxiality:

$$u_{\mathrm{f}} = \begin{cases} u_{\mathrm{f0}}\left(e^{-\frac{\sigma^{\mathrm{H}}}{\sigma_{\mathrm{eq}}}} - 1\right) + 1 & \text{if } \sigma^{\mathrm{H}} < 0 \\ 1 & \text{if } \sigma^{\mathrm{H}} \geq 0 \end{cases} \tag{8}$$

Where $\frac{\sigma^{\mathrm{H}}}{\sigma_{\mathrm{eq}}}$ represents the triaxiality and u_{f0} is a material parameter. Selecting $u_{\mathrm{f0}} = 0$ gives the same damage evolution under tension and compression. Increasing the value of u_{f0} diminishes the damage evolution under compression. The parameter u_{f0} can be determined using a compression test. In this work, the value of u_{f0} is taken high enough (see Figure 1) to produce negligible damage under negative triaxiality. This is a good assumption for ductile metals.

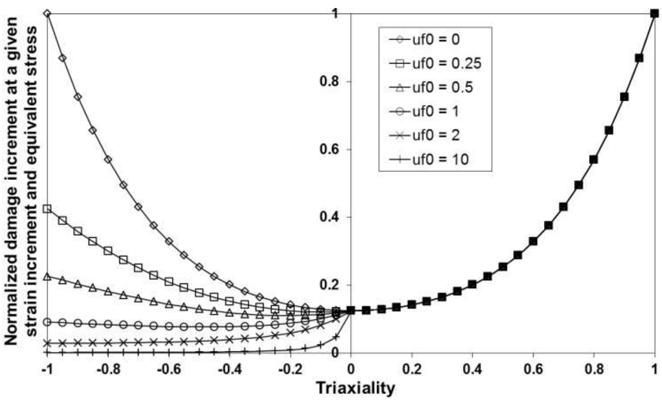


Figure 1: The effect of the parameter u_{f0} on the damage increment.

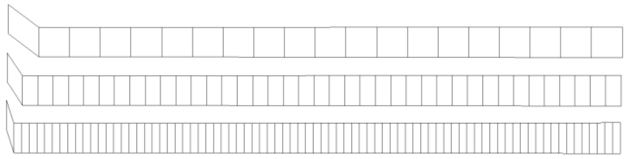
Damage development can also be rate dependent in ductile materials. The Dual Phase (DP) grades of steel are proven to be very useful in crash applications. These materials show enhanced post localization strains for higher strain rates [4]. Higher strain rates shift the thermodynamics of the deformation process from isothermal to adiabatic. Due to accumulation of heat at higher strain rates, the temperature of the material increases. This increases the ductility of the material and thus allows the voids to grow larger by delaying the void coalescence process and thus the initiation of a mesocrack. To avoid thermo-mechanical coupled simulations, damage is defined as a function of strain rate with an isothermal process assumption. To incorporate the delayed mesocrack initiation and slow damage evolution at large strain rates, the critical damage value D_{c} and material parameter s are made functions of strain rate.

$$D_{\mathrm{c}} = \max\left[D_{\mathrm{c0}}, \min\left[D_{\mathrm{c0}}\left\{\ln\left(\frac{1}{2} + \frac{\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{p}}}{2\dot{\varepsilon}_{\mathrm{r0}}}\right) + 1\right\}, 1\right]\right] \tag{9}$$

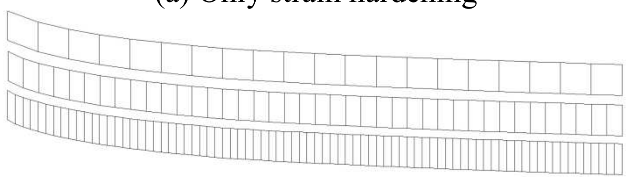
$$s = \min\left[s_0\left\{\ln\left(\frac{\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{p}} + s_0\dot{\varepsilon}_{\mathrm{r0}}}{\dot{\varepsilon}_{\mathrm{r0}}(1+s_0)}\right) + 1\right\}^{-\frac{1}{s_0}}, s_0\right] \tag{10}$$

Where D_{c0} and s_0 are the material parameters determined from a test at a reference average strain rate of $\dot{\varepsilon}_{\mathrm{r0}}$.

Viscoplastic regularization. Local continuum damage models are strain softening models which obey the principle of local action i.e. the constitutive behavior at a local point does not depend upon any action/variables at a distance (neighboring points). The problem with local behavior of a softening model is that as soon as a material point starts to soften, it takes up most deformation which leads to damage growth in that point, resulting in further softening. Therefore, once localization occurs, all the deformation accumulates in one element (or one row of elements). This makes the analysis mesh size dependent. However, viscoplastic regularization can be used to obtain objective results. The basic idea of viscoplastic regularization is that when the deformation rate starts to increase in the softer element (the element with damage), the increase in strain rate makes the element stiffer again. This phenomenon prohibits the deformation to accumulate in one element. Numerical studies were performed to check the effectiveness of viscoplastic regularization. The simplest case to study viscoplastic regularization is the one-dimensional shear test. The bar is fixed at one end and a vertical (y) displacement is prescribed at the other end. All nodes are fixed in horizontal (x) direction. The thickness of the bar decreases linearly from the free end to the fixed end. The non-uniform thickness will act as an imperfection hence the bar will localize at the fixed end. Figure 2(a) shows mesh dependent deformation for bar. All deformation localizes in one element at the fixed end. Figure 2(b) shows mesh independent deformation when strain rate hardening is added to the strain hardening part.



(a) Only strain hardening

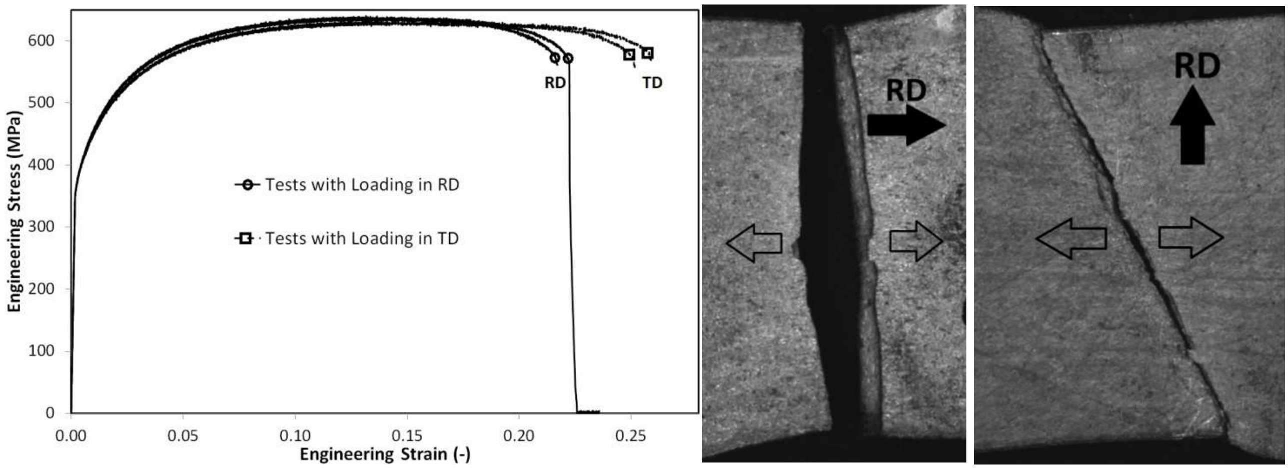


(b) Strain hardening + strain rate hardening

Figure 2: Bar (with imperfection) loaded in shear. Viscoplasticity regularizes the mesh dependency [5].

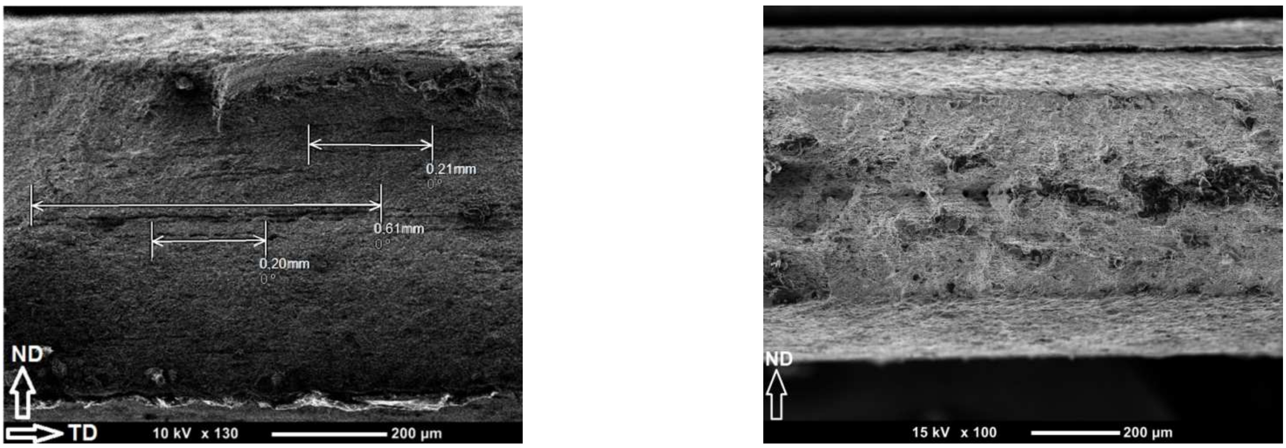
Material Induced Anisotropic Damage

The martensite morphology in DP600 was found to be anisotropic. The martensite is concentrated in the central region of the sheet thickness in the form of bands. The martensite bands aligned with the Rolling Direction (RD) of the sheet are longer compared to the martensite bands aligned with the Transverse Direction (TD). The anisotropic microstructure of the material induces anisotropy in the damage and failure behavior during deformation. Figure 3(a) shows the stress strain curves for tensile tests carried out on the material loaded in RD and TD. The material does not show anisotropic behavior up to localization. However, after localization the material fails earlier in RD compared to TD. Anisotropy can also be observed in the failure behavior of the material, see Figure 3(b). The fracture orientation is perpendicular to the loading when the sheet is loaded along the RD, whereas the fracture is inclined when loaded along TD. A through thickness shear failure can also be observed in the specimen loaded along RD, which is not the case for the specimen loaded along TD. The anisotropic failure behavior shown in Figure 3 is linked to an anisotropic damage behavior induced by the anisotropic martensite morphology. Figure 4 shows the fracture surface of the same specimens, which are shown in Figure 3(b). These specimens have entirely different damage distributions. In the specimen loaded along RD, a long central void coalescence can be observed. This central long coalescence weakens the material locally and fracture occurs by shear failure. Apart from this central coalescence, void concentration is very low



(a) Engineering stress engineering strain curves (b) Failure orientation

Figure 3: Results obtained from tensile testing of DP600, when loaded along RD and TD.



(a) Specimen loaded along RD (b) Specimen loaded along TD

Figure 4: Difference in void distributions in the fracture surface of the DP600 tensile specimens.

in the rest of the thickness in this specimen. On contrary, the specimen loaded in TD shows distributed voids along the fracture surface with a slightly higher concentration in the center. Most of the available anisotropic continuum damage models account for LIAD only, as the damage parameters used in the damage evolution law are direction independent. MIAD is included in Lemaitre's anisotropic damage model by making the damage dissipation potential F_{D} direction dependent

$$F_{\mathrm{D}} = \left(\frac{\bar{Y}}{S}\right)^{s} Y_{ij} \left|\mathbf{A}\colon\frac{\mathrm{d}\varepsilon^{\mathrm{p}}}{\mathrm{d}r}\right|_{ij} \tag{11}$$

where $\mathbf{A}$ is a fourth order MIAD tensor formed by MIAD parameters F_{A}, G_{A}, H_{A}, L_{A}, M_{A} and N_{A}, which gives a different damage evolution when the material is loaded in different orientation:

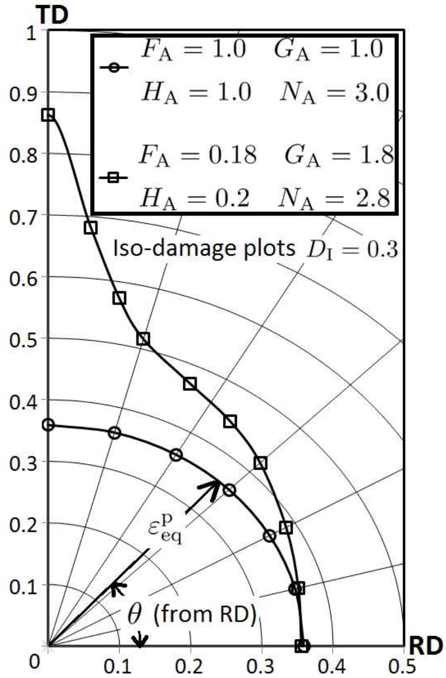


Figure 5: Direction dependent damage evolution

$$\dot{\mathbf{D}} = \left(\frac{\bar{Y}}{S}\right)^{s} |\mathbf{A}: \dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}| \quad (12)$$

Figure 5 shows the influence of MIAD parameters and loading angle from RD on the damage evolution. The two curves in Figure 5 represent the polar iso-damage plots for two different sets of MIAD parameters. The iso-damage plot is represented by the equivalent plastic strain, required to achieve a maximum principal damage value of 0.3. Further details of the MIAD behavior and MIAD model can be found in [3].

Validation of Modified Lemaitre's Anisotropic Damage Model

The model is intended for materials that are prone to damage when subjected to plastic deformation. Bearing in mind the objective and scope of the model, a 1 mm DP600 steel sheet metal grade was selected for validation. The damage parameters were determined using the fast identification method given by Lemaitre [1, 2]. The MIAD parameters were determined by fitting tensile tests carried out in 0°, 45° and 90° to RD of the sheet [3]. The complete set of damage parameters are given in Table 1. DP600 is plastically isotropic therefore Von Mises plasticity model was used in the simulations. The hardening of the material was defined with simplified Bergström van Liempt strain hardening model [6] and Krabiell-Dahl strain rate hardening model [7].

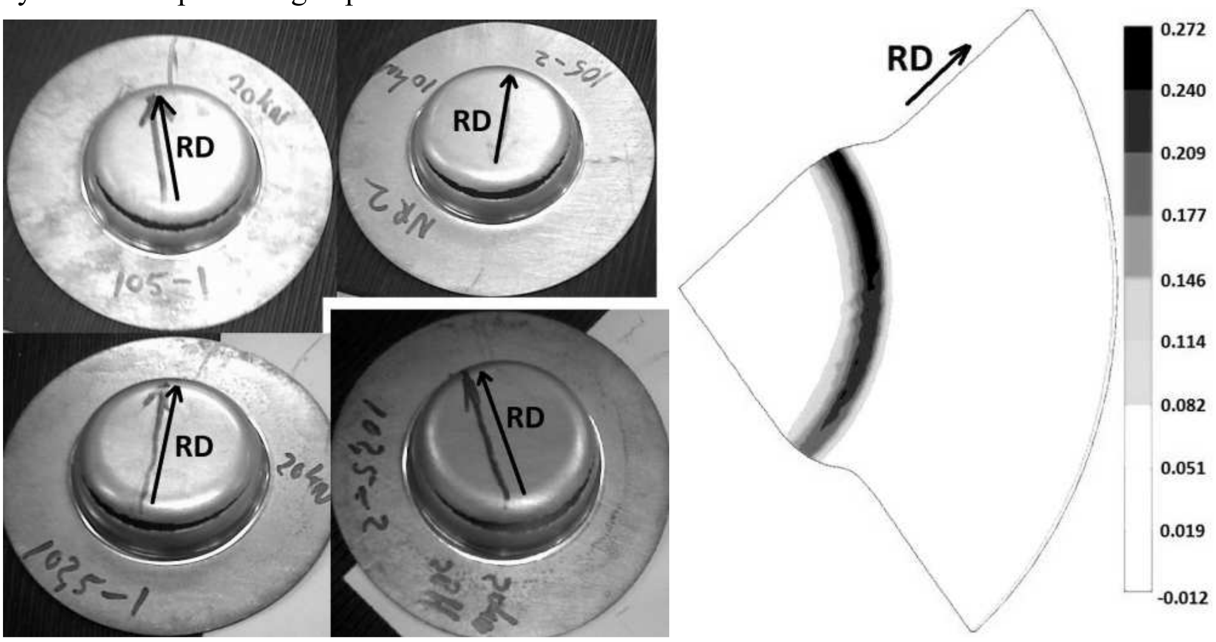
Table 1: Modified Lemaitre's anisotropic damage model parameters for DP600.

Parameter	$\varepsilon^{\mathrm{p}}_{\mathrm{D}}$	η	D_{c0}	S	s_0	$\dot{\varepsilon}_{\mathrm{r0}}$	u_{f0}	F_{A}	G_{A}	H_{A}	L_{A}	M_{A}	N_{A}
Value	0.18	3.0	0.18	1.4	2.3	0.001	50	0.18	1.8	0.2	3.0	3.0	2.8

Cylindrical cup drawing experiments were used for validation of the model. The axisymmetric characteristic of this test shall lead to a random orientation of failure with respect to the RD for plastically isotropic DP600 sheets. However, as mentioned earlier, the DP600 sheet material used in this research exhibits the phenomenon of MIAD which leads to a preferred orientation of failure for DP600 in cylindrical cup drawing. Figure 6(a) shows that the cylindrical cups made from DP00 have a preferred failure orientation in the RD of the sheet. Figure 6(b) shows the maximum principal damage obtained from the numerical simulation. The highest damage is found in the RD of the sheet which is in agreement with experiments. Prediction of this failure orientation would not be possible without the use of the MIAD model.

Conclusion

The standard Lemaitre anisotropic damage model was modified to incorporate: lower damage evolution under compression, strain rate dependency in damage and Material Induced Anisotropic Damage (MIAD). DP600 shows the phenomenon of MIAD, which is linked to the anisotropy in martensite morphology. The model has been validated especially for MIAD using the cylindrical cup drawing experiments.



(a) Experiments results (b) Maximum principal damage in simulation

Figure 6: Failure orientation in DP600 cylindrical cup drawing test.

This research was carried out under the project number M61.1.08308 in the framework of the Program of the Materials innovation institute M2i (www.M2i.nl).

References

[1] J. Lemaitre and R. Desmorat. Engineering Damage Mechanics. Springer, 2005.
[2] Niazi, M.S., Wisselink, H.H., Meinders, T., & Huetink, J. (2012). Failure predictions for DP steel cross-die test using anisotropic damage. International Journal of Damage Mechanics, 21(5), 713-754.
[3] Niazi, M.S., Wisselink, H.H., Meinders, T., & Boogaard van den, A.H. (2012). Material induced anisotropic damage in DP600. International Journal of Damage Mechanics, accepted for publication.
[4] H. Huh, S. B. Kim, J. H. Song, and J. H. Lim. Dynamic tensile characteristics of TRIP-type and DP-type steel sheets for an auto-body. International Journal of Mechanical Sciences, 50:918–931, 2008.
[5] Niazi, M.S., Wisselink, H.H., & Meinders, T. (2012). Viscoplastic regularization of local damage models: revisited. Computational mechanics, doi:10.1007/s00466-012-0717-7
[6] P. van Liempt. Work hardening and substructural geometry of metals. Journal of Materials Processing Technology, 45:459–464, 1994.
[7] A. Krabiell and W. Dahl. Zum einfluss von temperatur und dehngeschwindigkeit auf die streckgrenze von baustählen unterschiedlicher festigkeit. Archiv für das Eisenhüttenwesen, 52:429–436, 1981.