Formability prediction for AHSS materials using damage models

R. Amaral¹, Abel D. Santos², José César de Sá² and Sara Miranda¹

¹ Institute of Science and Innovation in Mechanical and Industrial Engineering, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
² Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias 400, 4200-465 Porto, Portugal

E-mail: ramaral@inegi.up.pt, abel@fe.up.pt, cesarsa@fe.up.pt, smiranda@inegi.up.pt

Abstract. Advanced high strength steels (AHSS) are seeing an increased use, mostly due to lightweight design in automobile industry and strict regulations on safety and greenhouse gases emissions. However, the use of these materials, characterized by a high strength to weight ratio, stiffness and high work hardening at early stages of plastic deformation, have imposed many challenges in sheet metal industry, mainly their low formability and different behaviour, when compared to traditional steels, which may represent a defying task, both to obtain a successful component and also when using numerical simulation to predict material behaviour and its fracture limits. Although numerical prediction of critical strains in sheet metal forming processes is still very often based on the classic forming limit diagrams, alternative approaches can use damage models, which are based on stress states to predict failure during the forming process and they can be classified as empirical, physics based and phenomenological models. In the present paper a comparative analysis of different ductile damage models is carried out, in order numerically evaluate two isotropic coupled damage models proposed by Johnson-Cook and Gurson-Tvergaard-Needleman (GTN), each of them corresponding to the first two previous group classification. Finite element analysis is used considering these damage mechanics approaches and the obtained results are compared with experimental Nakajima tests, thus being possible to evaluate and validate the ability to predict damage and formability limits for previous defined approaches.

1. Introduction

Sheet metal formability can be defined as the ability of metal to deform without necking or fracture into a desired shape. Every sheet metal can be deformed without failing only up to a certain limit, which is normally known as forming limit curve (FLC). Usually it is experimentally determined for defined linear strain paths, by using Marciniak tests, where a sheet metal sample is strained by a flat-bottomed cylindrical punch having a frictionless in-plane deformation, or by using Nakajima tests, in which the sample is deformed by an hemispherical punch (out-of-plane) and by varying the sample width, different linear strain paths can be obtained.

The experimental determination of FLC for sheet metal is time consuming and requires expensive equipment. Because of the expenses involved on the experimental procedure, many mathematical criteria for plastic instability have been proposed, empirically as well as theoretically [1, 5], to predict the forming limits of the metallic material, making these methods very attractive. However, since these models don’t take into consideration the variation of
the strain path and microscopic damage, some authors proposed modifications, by considering such variation during the deformation [6, 7], or by introducing new models [8], like a new path independent failure criterion to predict necking in sheet metal forming.

Another possible approach is considering damage models based on stress state to predict failure during the forming process. These damage models can be classified as empirical, physics based and phenomenological [9, 10].

In this work two different ductile damage models were selected, Johnson-Cook and GTN, each of them corresponding to the previous group classification, to predict the forming limit curve of a dual-phase steel (DP780). The selected models, namely GTN and Johnson-Cook, are already available in finite element program Abaqus.

To study the previous damage models, a dual-phase DP780 steel with a nominal thickness of 0.8 mm was selected and the corresponding experimental forming limit curve was obtained. A detailed description of the procedure will be presented in further section.

Also in this work, finite element simulations of Nakajima test were carried out and the obtained results were compared with experimental FLD, as well as, the punch force vs. displacement curves, in order to evaluate the implemented ductile damage models and their ability to predict the material forming limit.

2. Damage models

Gurson Tvergaard Needleman (GTN) damage model is used to determine the forming limit curve of anisotropic sheet metals. The original model proposed by Gurson [11] was further extended by Tvergaard and Needleman [12, 13] replacing the variable \( f \) by a modified parameter \( f^* \) in order to take into account the accelerated void coalescence process after a critical void volume fraction \( f_c \) is reached. The yield function of the GTN damage model is given by:

\[
\phi = \left( \frac{\sigma}{\sigma_Y} \right)^2 + 2q_1 f^* \cosh \left( \frac{3}{2} q_2 \frac{\sigma_H}{\sigma} \right) - \left( 1 + q_3 f^* \right)
\]

where \( q_1, q_2 \) and \( q_3 \) are the model parameters, \( \sigma_Y \) the flow stress and \( \sigma_H \) and \( \sigma \) the hydrostatic stress and equivalent von Mises stress, respectively. The modified porosity parameter \( f^* \) is calculated by:

\[
f^* = \begin{cases} 
  f & f \leq f_c \\
  \frac{1}{f_c} + \frac{1}{f_c} (f - f_c) & f > f_c
\end{cases}
\]

The evolution law of the void volume fraction \( \dot{f} = \dot{f}_G + \dot{f}_N \) take into account the void growth and nucleation, both variables expressed, respectively, by:

\[
\dot{f}_G = (1 - f) \text{tr} \dot{\varepsilon}_p
\]

\[
\dot{f}_N = \frac{f_N}{S_N \sqrt{2\pi}} \exp \left[ - \frac{1}{2} \left( \frac{\dot{\varepsilon}_p - \varepsilon_N}{S_N} \right)^2 \right] \dot{\varepsilon}_p
\]

where \( f_N, S_N \) and \( \varepsilon_N \) are material parameters and \( \dot{\varepsilon}_p \) is the plastic strain rate tensor.

The model proposed by Johnson and Cook [14] has material degradation under plastic deformation expressed by damage indicators, which, besides the postulation of a phenomenological strain rate and temperature dependent hardening law, defines the fracture strain \( \varepsilon_f \) as a function of stress triaxiality \( \eta \), plastic strain rate \( \dot{\varepsilon}_p \) and temperature \( \theta \) as:
\[ \varepsilon_f = \left( d_1 + d_2 \cdot e^{d_3 \eta} \right) \left[ 1 + d_4 \ln \left( \frac{\varepsilon_p}{\varepsilon_0} \right) \right] (1 + d_5 \theta) \]  

(4)

where \( d_1, d_2, d_3, d_4 \) and \( d_5 \) are material parameters.

3. Material mechanical characterization

The material used in this work is a dual-phase DP780 steel sheet with a thickness of 0.8 mm. Scanning electron microscopy (SEM) observations were performed on the initial material (figure 1) showing that the microstructure is defined by the presence of hard martensite particles (lighter areas) dispersed in the soft ferritic matrix [15, 16].

The average size of ferritic grains \((D)\) and the volume percentage of martensite \((V_M)\), obtained from microstructural observations is presented in table 1.

\begin{table}[h]
\centering
\begin{tabular}{lcc}
\hline
Material & D (\(\mu\)m) & V_M (\%) \\
\hline
DP780 & 6 & 25 \\
\hline
\end{tabular}
\caption{Average size of ferritic grains \((D)\) and volume percentage of martensite \((V_M)\) in DP780 steel [15, 16].}
\end{table}

Figure 1: SEM images of DP780 steel [15, 16].

Uniaxial tensile tests were performed at room temperature using a defined 0.0016 s\(^{-1}\) initial strain rate. Specimens have been machined according to ASTM E 8M-04 standard and the tests were conducted for three different directions relative to the rolling direction \((0^\circ, 45^\circ \text{ and } 90^\circ)\).

Results were averaged from three experiments for each direction, in order to test and ensure repeatability. Figure 2 shows the true stress vs. strain hardening curves for DP780, according to the defined loading directions. Additionally, hydraulic biaxial bulge tests of DP780 were also performed, being the biaxial stress vs. strain curve presented in Fig. 3.

Figure 2: Tensile true stress vs. strain curves of DP780 for different loading directions.

Figure 3: Biaxial stress vs. strain curve from bulge test of DP780.
The mechanical properties acquired from tensile tests are presented in table 2, namely yield stress (YS), ultimate tensile strength (UTS), elongation at yield point (e₀), uniform elongation (eᵤ) and total elongation (eₜ), as well as, the anisotropic coefficients measured for the same evaluated loading directions.

| Direction | YS [MPa] | UTS [MPa] | e₀ [%] | eᵤ [%] | eₜ [%] | r-value |
|-----------|----------|-----------|--------|--------|--------|---------|
| 0°        | 526.18   | 843.10    | 0.47   | 12.53  | 17.96  | 0.70    |
| 45°       | 537.72   | 845.87    | 0.49   | 11.78  | 18.10  | 1.05    |
| 90°       | 517.78   | 840.95    | 0.49   | 12.35  | 18.04  | 0.88    |

In order to describe the hardening behaviour of the DP780, the Swift Law was used. The identified parameters are presented also in table 3.

Table 3: Swift law parameters for DP780 steel.

\[
\sigma = K (\varepsilon_0 + \varepsilon^p)^n
\]

| K [MPa] | \( \varepsilon_0 \) | n |
|---------|---------------------|---|
| 1319.2  | 0.0015              | 0.149|

3.1. Parameters of Damage models

For the Johnson-Cook damage model, strain rate and temperature effects were not considered, corresponding to parameters \( d_4 \) and \( d_5 \), respectively. In these model the failure strain depends the stress triaxility so it’s important the determination of parameters \( d_1, d_2 \) and \( d_3 \).

To characterize the damage behaviour of the material DP780 using the selected damage models, the corresponding parameters were identified through an inverse optimization FE methodology. The procedure uses as reference the tensile and biaxial bulge test data to find the optimum fitting parameters, which represents the best correlation between numerical and experimental curves.

Since the strain rate and temperature effects of Johnson-Cook damage model were not considered, the parameters \( d_4 \) and \( d_5 \) were not included in the identification scheme.

In case of GTN, the standard deviation \( S_N \) was set to 0.2 which is often used by other authors in literature. Moreover, the values of parameters \( q_1 \) and \( q_2 \)

Furthermore, the values set for parameters \( q_1 \) and \( q_2 \) were based on characterizations conducted by others, in order to reduce the number of variables to be identified.

The parameters used for Lemaitre damage model has been identified by Niazi et al [16]. Table 4 presents the parameters of each ductile damage model.
Table 4: Implemented damage model parameters (DP780).

| GTN damage model | Parameters | $q_1$ | $q_2$ | $q_3$ | $f_c$ | $f_F$ | $\varepsilon_N$ | $S_N$ | $f_N$ |
|------------------|------------|-------|-------|-------|-------|-------|-----------------|-------|-------|
| Values           | 1.5        | 1     | 2.25  | 0.021 | 0.04  | 0.3   | 0.1             | 0.001 |

| Johnson-Cook damage model | Parameters | $d_1$ | $d_2$ | $d_3$ | $d_4$, $d_5$ |
|---------------------------|------------|-------|-------|-------|--------------|
| Value                     | 0.94       | -0.29 | 6.48  | 0     |

4. FLD experimental determination

Nakajima et al. [17] proposed to use metal sheet strips with different widths, stretched by a hemispherical punch (figure 4), in order to obtain the material forming limit curve. By varying the sample width, different strain paths can be achieved (figure 5).

![Figure 4: Tool dimensions and FLD setup used in Nakajima tests.](image1)

![Figure 5: Obtained FLC points for different specimen widths.](image2)

The Nakajima testing procedure uses a hemispheric punch of 101.6 mm diameter and drawbeads in tools, to restrain the blank between the die and blank-holder and also to avoid stress concentration at the transition from strip section to the blank. Nakajima experiments were performed according to the standard ISO 12004-2 [18], to measure the DP780 formability, as well as to determine the corresponding forming limit curve. To obtain a wide range on forming limit curve the specimen widths are varied and then different strain paths and values are obtained. The defined specimens for testing have the following widths: 25, 50, 75, 100, 125 and 175 mm [19, 20].
All experimental tests were conducted on a hydraulic testing machine, as seen in figure 6. The tooling setup is interchangeable depending on the type of experiments. The friction between punch and blank was minimized by applying a teflon foil at the top of the punch, in addition to a lubricant at the sheet surface (Ferrocoat N 6130). Necking or fracture visualization determined the moment to stop the test.

Strain measurements on samples can be done through several methods, but in this paper the method used was a variant of Bragard method [21], which it is applicable to perform measurements on grids of tangled circles, obtained in this work by an electrochemical etching process. For interpolation, it was followed the recommendation of using the circles whose deformation differences of adjacent circles is less than 5%.

The obtained experimental data points are represented by fitting curve that has been adjusted, using the least square approximation approach. This methodology performs an adjustment for the drawing region and another for the stretching region. The figure 8 shows the forming limit curve of the studied dual-phase material and corresponding experimental points.

![Image](image_url)

**Figure 6:** Universal testing machine used for Nakajima test and FLD determination.

![Image](image_url)

**Figure 7:** DP780 experimental points and corresponding fitting curve.
The FLC$_0$ point can be determined experimentally from a tensile test of a large width specimen or using a smaller range of Nakajima specimens widths in plane strain region. A mathematical expression (equation 5) based on material thickness ($t$) and hardening coefficient ($n$) can be used to obtain a reference FLC$_0$ value [22, 23].

$$FLC_0 = \ln \left[ 1 + \left( \frac{13.3 + 14.13 \cdot t}{100} \right) \frac{n}{0.21} \right]$$

for $n \leq 0.21 \Leftrightarrow FLC_0 = 0.16 \quad (5)$

The experimental FLC$_0$ point was obtained by the interception of the fitting curves and its value is 0.152, showing a good agreement with the analytical result.

Figure 8 shows the corresponding specimens fractured during the experimental Nakajima tests. The necking and fracture occur at the dome thus showing that friction was minimized. Since this test is affected by the friction between the punch head and the specimen when contacted, the sheet deformation could be limited to the regions in contact with the punch.

![Figure 8: Obtained FLC points for different specimen widths.](image)

5. Finite Element Analysis

Numerical simulations were performed using a 3D finite element explicit analysis with Abaqus/Explicit code and defining a full model for the Nakajima test (figure 9).

The blank was discretized by four node shell elements with reduced integration (S4R type from Abaqus Library) and tools were discretized by analytical rigid surfaces. A constant friction coefficient of 0.05 was defined for the interacting surfaces. As for the material mechanical modelling, the sheet blank is defined as an elasto-plastic material with isotropic hardening defined by the constitutive model already presented in section 3. Johnson-Cook and GTN ductile damage models are available in FE program.
6. Results and Discussion

Limit strain values from the numerical simulation were obtained using the same experimental methodology. Each ductile damage model FLC was formed by a fitted curve to the strains points acquired from different sample widths (as seen in figure 10) using the least-squares method. The comparison of DP780 forming limit curves, determined experimentally and using the ductile damage models is shown in figure 11.

Globally, the forming limit curves obtained from numerical simulation using the damage models and presented in figure 11 show a similar tendency compared to the experimental data. The GTN criterion prediction of forming limit curve gives closer results when compared with experimental data. In case of Johnson-Cook damage model, the numerical points are more dispersed.

The Johnson-Cook and GTN damage models seem to have a lower formability in plane strain state and also in the stretching region, being more evident in equibiaxial loading case. This trend, more evident in Johnson-Cook damage model, which shows closer results to experimental data.
points in left FLD region and an underestimation of forming limits in right side, can be adjusted by the user, since this model expression is an exponential based formula. Due to the influence of experimental reference data used to identify the model parameters, a closer fitting to some part of FLC could be made.

By comparison of the formability prediction of DP780 using these two ductile damage models with experimental results, it can be concluded that the GTN model gives a better approximation and shows a closer overall prediction to current experimental data. However, with a smaller initial relative density, the formability prediction of GTN can be increased and the FLC could be more closer in plane strain and stretching region (right side of FLD) but a possible overestimation in drawing region (left side of FLD) could be happen.

Additionally to this study, a comparison of punch force vs. displacement curves were performed, in order to evaluate the numerical and experimental data, being also a complement to the FLD analysis.

Figure 12 shows the curves of punch force vs. displacement evolution during deformation for each sample width defined in this work. Numerical results for current damage models and experimental data are compared on the same graph.
Figure 12: Comparison of experimental punch force evolution for different specimen widths, with the numerical results from the damage models.

Figure 12 presents the evolution of the punch force vs. displacement during forming process...
where experimental data and numerical results are compared.

It can be observed that the evolution of punch force predicted is very similar to the experimental punch force. Additionally, this comparison allows the evaluation of punch stroke at which fracture occurs.

Since GTN damage model has a closer forming limit curve to the experimental data, the punch stroke is in a very good agreement with experimental observation. In contrast, the Johnson-Cook model shows a smaller value of punch stroke for all of defined sample widths.

7. Conclusions

In this paper, two different ductile damage models, Gurson-Tvergaard-Needleman (GTN) and Johnson-Cook, were used to predict the forming limit curve of a dual-phase DP780 steel sheet with a nominal thickness of 0.8 mm. Their ability to reproduced the material behaviour was analysed and validated using the Nakajima experimental test, for different specimen geometries, as a reference.

The FLD of DP780 using the damage models was formed through a set of Nakajima finite element simulations, which GTN numerical prediction showed a good agreement with the experimental results. In general, the forming limits predicted by the GTN model were more closer than those obtained with the Johnson-Cook damage model. The parameters used for Johnson-Cook damage model provided smaller forming limits of the DP780 steel and consequently an underestimation of material formability.

A comparison of punch force vs. displacement was made between the finite element results obtained from the two models and the experimental data. The analysis of results shows that the punch force evolution is very close to the experiment, for all tested specimen widths. However, the Johnson-Cook damage model predicted a smaller punch force, since the damage of material happened at an earlier stage and consequently a smaller punch stroke.

Further studies will include the influence of damage parameters identification and also the friction model considered in numerical simulation results.

7.1. Acknowledgments

Authors gratefully acknowledge the funding of SciTech, R&D project NORTE-01-0145-FEDER-000022 cofinanced by NORTE2020, through FEDER and the financial support of the Portuguese Foundation for Science and Technology (FCT) under project PTDC/EMS-TEC/6400/2014. The first author is also grateful to the FCT for the Doctoral grant SFRH/BD/119362/2016.

References

[1] A. Col: "FLCs: Past, present and future", IDDRG 2002 Conference, Nagoya, Japan, 107-25 (2002).
[2] D. Banabic: "Sheet Metal Forming Processes - Constitutive Modelling and Numerical Simulation", Springer-Verlag GmbH, (2010).
[3] A. Hrivnak, E. Evin: "Formability of steel sheets", Kosice: Elfa, (2004).
[4] Morteza Nurcheshmeh: "Numerical prediction of sheet metal forming limits", Dissertation, University of Windsor, (2011).
[5] A. Pradeau, S. Thuillier and J.W. Yoon, Prediction of failure in bending of an aluminium sheet alloy, International Journal of Mechanical Sciences, 119, 23-35 (2016).
[6] P. Hora, L. Tong, J. Reissner: "A prediction method for ductile sheet metal failure in FE-simulation", Proceedings of the Numisheet96 Conference (Dearborn/Michigan), 252-56 (1996).
[7] Z. Marciniak, K. Kuczynski: "Limit strains in the processes of stretch forming sheet metal", International Journal of Mechanical Sciences, 9(9), 609-612 (1967).
[8] T.B. Stoughton and J.W. Yoon, A new approach for failure criterion for sheet metals, International Journal of Plasticity, 27(3), 440-59 (2011).
[9] Y. Bai and T. Wierzbicki, A comparative study of three groups of ductile fracture loci in the 3D space, Engineering Fracture Mechanics, 135, 147-67 (2015).
[10] T. Wierzbicki, Y. Bao, Y.W. Lee, Y. Bai, Calibration and evaluation of seven fracture models, International Journal of Mechanical Sciences, 47(4-5), 719-43 (2005).
[11] L. Gurson, Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I-Yield Criteria and Flow Rules for Porous Ductile Media, Journal of Materials Processing Technology, 99, 2-15 (1977).
[12] V. Tvergaard, On localization in ductile materials containing spherical voids, International Journal of Fracture, 18, 237-52 (1982).
[13] V. Tvergaard and A. Needleman, Analysis of the cup-cone fracture in a round tensile bar, Acta Metallurgica, 32, 157-69 (1984).
[14] G.R. Johnson, W.H. Cook, Engineering Fracture Mechanics, 21, 31-48 (1985).
[15] R. Amaral, H. Campos, J.A. Sousa, A.B. Lopes, A.D. Santos: "Inovação em Materiais: Aços Bifásicos - DP500, DP600, DP780, caracterização mecânica e microestrutural", TECNOMETAL (AIMMAP - Associação dos Industriais Metálicos, Metalomecânicos e afins de Portugal), 218, 4-9 (2015).
[16] R. Amaral, A.D. Santos, J.A. Sousa, A.B. Lopes: "The Influence of Microstructure on the Mechanical Behaviour of Dual Phase Steels", Materials Design and Applications, 65(3) (2017).
[17] K Nakajima, T Kikuma, and K Hasaku: "Study of the formability of steel sheets". Yawata Technical Report No.264, 141-54 (1968).
[18] ISO 12004 standard: Metallic materials guidelines for the determination of forming limit diagrams, (2008).
[19] M. Parente, R. Safdarim, A.D. Santos, A. Loureiro, P. Vilaca, R.M Natal Jorge: A study on the formability of aluminum tailor welded blanks produced by friction stir welding, International Journal of Advanced Manufacturing Technology, 83, 2129-41 (2016).
[20] R. Safdarian, H. Moslemi Naeini, R.M. Natal Jorge, A.D. Santos, M.P.L Parente: A comparative study of forming limit diagram prediction of tailor welded blanks, International Journal of Material Forming, 8(2) (2014).
[21] A. Bragard, J.C. Baret, H. Bonnarens, Metallurgical Rap. CRM, 33, 53-63 (1972).
[22] S.P. Keeler, W.G. Brazier, Relationship between laboratory material properties and press shop formability, Proceedings of conference on microalloy, 75, 517-28 (1977).
[23] S.K. Paul: Theoretical analysis of strain- and stress-based forming limit diagrams, Journal of Strain Analysis for Engineering Design, 48(3), 177-88 (2013).