Damage Curve Determination of Dual Phase Steel Based on GTN Mode-l Failure Criteria

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***Abstract*—Dual phase steels are gaining a wide array of applications in the automotive engineering fields and can be subjected to forming/stamping process due to their good mechanical properties. However, it shows complex damage mechanism resulting intricate prediction of sheet formability. In this study, the mechanical Gurson-Tvergaard-Needleman (GTN) model was used to develop Damage Curve due to the GTN model is the micromechanical damage which is widely used for predict formability of Dual Phase steel by calculating the evolution of voids in the matrix. To adequate calibration of GTN parameters were defined by sufficiently comparative method between mechanical behaviors and numerical analysis, however, the accuracy of determined parameters was verified by different stress states on the tensile test of different specimen together with numerical simulation. The accurate results show a good agreement of force-displacement response. On the part of the damage curve development, it uses Hybrid method by considering tensile tests of various sample geometries. The results showing the relation between the equivalent strain to localized necking and an initial crack of versus the stress triaxialities represented that the GTN model and others criteria directly effect on all range of stress triaxialities.**

***Index Terms*—damage curve, dual phase steels, GTN model, numerical analysis**

I. INTRODUCTION

Nowadays, dual phase steels have been increasingly applied in the automotive industries for vehicle mass reduction [1]. Due to dual phase steels characteristic influence on damage mechanisms making the prediction of material formability difficultly moreover while these steel has been deformed by mechanical loading, the strain was concentrated in the lower strength ferrite phase surrounding the islands of martensite [2], [3]. The complex mechanisms of this steel type, ductile failure mechanism, the void nucleation takes places not only at the interface between the phase which can cause the cracking of the martensite but also at inclusion and precipitation areas. In case of the forming process, small post-necking deformation was observed, so fracture could even occur before strain localization. The crack initiation can take place in dual phase steel before necking and it tends to occur a macrocrack at an early state. To predict material behavior, the micromechanical Gurson-Tvergaard-Needleman (GTN) damage model [4]-[7] is one of the ductile failure criterions having been used to describe the ductile failure mechanism of the dual phase steel by calculating the evolution of voids in a matrix due to applied mechanical loading. In this research, the parameters of GTN model for dual phase steels grade DP780 was determined by numerical investigation using unit cells and experimental fitting as Ole west [8] done to develop the damage curve.

$$\Phi = \left(\frac{\sigma_v}{\sigma_y}\right)^2 + 2 \cdot q_1 \cdot f^* \cdot \cosh\left(\frac{3}{2} \cdot q_2 \cdot \frac{\sigma_h}{\sigma_y}\right) - \left(1 + q_3 \cdot f^{*2}\right) = 0 \quad (1)$$

GTN model: According to damage curve was developed in this study by using the Gurson-Tvergaard and Needleman model as failure criteria being a one of the micromechanical models, used to predict the formability of ductile material by explaining the three failure mechanisms: nucleation, growth and subsequent coalescence of voids within the matrix of dual phase steel gradually leading to the failure due to mechanical loading. This model can be described, as in Eq. 1. Where, σ_v is von Mises equivalent stress, σ_h is Hydraulic stress component, σ_y is Yield stress of the matrix material, f^* is Damage function of Micro-void volume fraction or porosity (f) and q_1, q_2 , q_3 are Adjustment parameters added by Tvergaard and Needleman in order to avoid overestimation between experiment and unit cell simulation.

$$f^*(f) = \begin{cases} f & ; f > f_c \\ f_c + K(f - f_c) & ; f > f_c \end{cases} \quad (2)$$

$$K = \frac{f_u^* - f_c}{f_f - f_c};\ f_u^* = \frac{q_1 - \sqrt{q_1^2 - q_3}}{q_3};\ q_3 = (q_1)^2 \quad (3)$$

$$\dot{f} = \dot{f}_{growth} + \dot{f}_{nucletion}$$
$$\dot{f} = (1 - f_0) \cdot \dot{\varepsilon}_{kk} + \frac{f_N}{S_N \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{1}{2}\left(\frac{\bar{\varepsilon} - \varepsilon_N}{S_N}\right)^2\right) \cdot \dot{\bar{\varepsilon}} \quad (4)$$

Considering the equation, if the function of the void volume fraction reduces to zero, the model will become the standard von Mises yield criteria. The micro-void volume fraction or porosity can explain in Eq. 2-3, and the void evolution law can explain in Eq. 4, showing growth function and nucleation function. Where, f_0 is

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Influence of initial void volume fraction, f_N is Secondary void volume fraction, S_N is Standard deviation of void development, ε_N is Characteristic of plastic strain. As mentioned above, the seven major parameters of GTN damage model (f_0 , q_1, q_2, q_3, f_c, K, ε_N and f_N) were determined by numerical analysis compared with the experimental result, as follows.

II. Experimental and Results

Initial void volume fraction (f_0): Firstly, the initial void volume fraction was defined to be primary void volume fraction in the matrix of material by calculating the volume ratio of void to unit cell (Vvoid /Vunitcell), so the initial void volume fraction was set equal to 0.0003, often used in ductile steel, however, if the initial void volume fraction has excessive value, it affects poor mechanical properties, and if the initial void volume fraction was set to zero, the mechanical properties will depend on void nucleation factors.

Critical void volume fraction (f_C), factor (K) and Adjustment parameters (q_1, q_2, q_3): The critical void volume fraction were calibrated by fitting under maximum equivalent strain ($\varepsilon<\varepsilon_M$) with the unit cell consisting of one axisymmetric element simulation based on GTN model yield criteria by examined the four different stages of stress triaxiality (1, 1.5, 2 and 2.5) and using the unit cell containing a spherical explicit void simulation (2D) as a reference for comparison. The two different uniform loads ratio of unit-cell can calculate by using Eq. 4.

$$\alpha = \frac{F_1}{F_2} = \frac{3\eta - 1}{3\eta + 2} \tag{5}$$

As shown in Fig. 1-Fig. 2, it demonstrates the comparable results of fitting parameters under four stress triaxialities by numerical simulation via stress-strain curve and the development of void volume fraction curve. At the different stage of stress triaxiality, it shows similar slope, the rate of void volume fraction had stably increased until the point of maximum stress. The slop of void evolution is accelerated. After the cell collapse, and the void volume fraction significantly increases while the equivalent stress dropped in linear function, therefore, the results show that the stress triaxialities influence on the changing-behavior of void volume fraction and equivalent plastic strain.

$$\Delta q_i = \frac{1}{f_c^{uc}} \int_0^{uc} \left(f_{void}^{uc} - f_{GTN}^{uc}(q_i) \right) \cdot \dot{\varepsilon} \rightarrow \min \tag{6}$$

Regarding the adjustment parameters, it was fitted by means of the minimizing the fitting error, explained as Eq. 5 in order to find the proper adjustment parameters, The best result in this study is q_1 = 1.35 and q_2 = 0.88, even though, the recommended parameter pair is q_1 =1.5 and q_2 =1, proposed by Tvergaard and Needleman, And to determine K factor, it was fitted by using the same method as finding the critical void volume fraction. The appropriate factor K is 3.5 for all stress triaxialities.

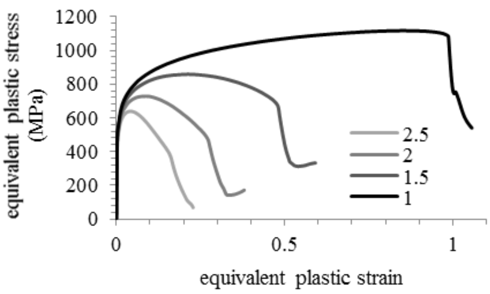

Figure 1. Equivalent stress-strain curve of unit cell with explicit void simulations.

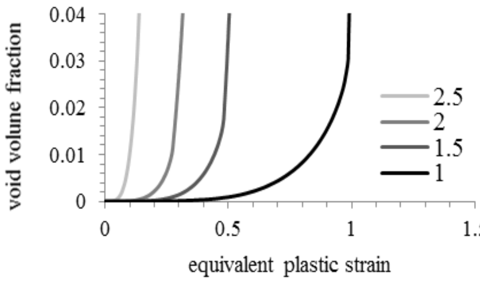

Figure 2. The development of void volume fraction of unit cell with explicit void simulations.

Characteristic plastic strain of secondary void nucleation (ε_N): The characteristic plastic strain of secondary void nucleation was fitted by using plane strain specimen for tensile test simulation analysis and experimental tensile test combined with direct current potential drop method (DCPD) extensively used to investigate the micro-crack in the ductile material based on electrical principle. During tensile test, giving mechanical loading on specimen, the electrical resistance will drop while the void nucleation takes place in the specimen. The changed electric potential will be measured. It will clearly show the variation of characteristic loading at secondary void nucleation which is identified as the point of characteristic plastic strain of secondary void nucleation on numerical simulation analysis based on GTN model result, therefore, the characteristic plastic strain of secondary void is 0.083.

Standard deviation (S_N): The standard deviation, negligible value, used to describe the normal distribution of the void nucleation, was set to 0.2 which is often used as shown in literature review [9].

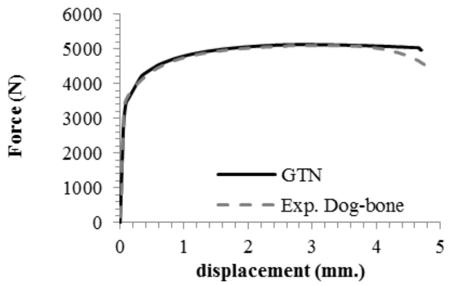

Figure 3. Force-displacement curve of dog-bone specimen experimental result and simulation result.

Secondary void volume fraction (f_N): In order to fit the secondary void volume fraction, it can be determined by using different flat tensile test specimens, the dog-bone specimen and central-hole specimen, ASTM standard conditions, for experimental testing and as a model for numerical simulation based on GTN model criteria. The force-displacement curves results from both simulation and experiment were compared so as to get the best fitting result of secondary void volume fraction which is 0.002 for this study. Fig. 3 shows the good relation of force-displacement curves between simulation result and experimental result which reveals to the accuracy of the determined variable.

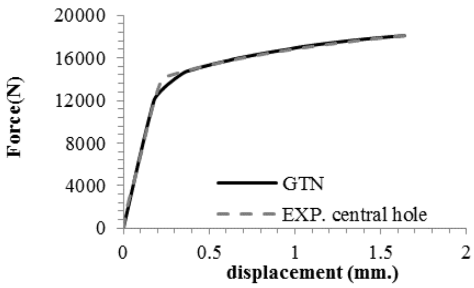

Figure 4. Force-displacement curve of central- hole experimental result and simulation result.

Damage curve determination: The Damage curve is explained relation between the stress triaxiality and the equivalent plastic strains. Bao and Wierzbicki [10] proposed that the stress triaxiality is significant parameter governing crack initiation besides the equivalent strain. The damage curve in this study, concerning with only positive stress triaxiality (0-0.8) of dual phase DP780, was developed at crack initiation and localize necking by using hybrid method [11], experimental tensile test of various sample geometry with DCPD and numerical simulation. At high stress triaxiality (0.3-0.6) are identified by using tensile specimen (uniaxial, Radius, U-, C- and V-notch specimen), in contrast, the pure shear and combined loading specimen were used to identify in low stress triaxiality (0.02-0.15). The equivalent plastic strain was identified at the highest stress triaxiality point on the middle path of each specimen at the initial crack time and at the first stages of localized necking time. Finally, the result of the developed damage curve by using GTN indicates the plastic strain through positive stress triaxiality, compared with the results from others yield criteria and experimental tensile tests, represented in Fig. 4

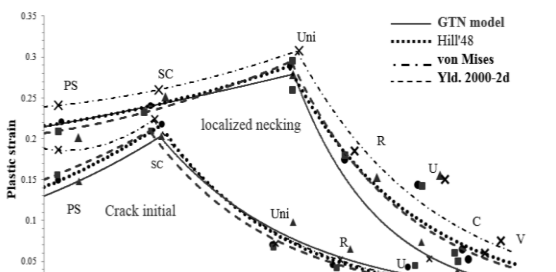

Figure 5. Determined damage curves for crack initiation and localized necking using different yield criteria.

III. Summary

As a results, the development of damage curve based on both crack initial and localized necking which uses the GTN model failure criteria compared with others yield criteria, the results of damage curve using GTN model was found that the localized necking was lower than the other yield criteria all range of stress triaxiality values. On the other hand, the damage curve for crack initiation was lower than all range of high stress triaxialities. But it was not different curve in low stress triaxiality range. Moreover, there are two distinct branches of this function with possible slop discontinuities in for large triaxiality void growth is the dominant failure mode

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