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# Damage evolution and void coalescence in finite-element modelling of DP600 using a modified Rousselier model

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ABSTRACT

Numerical simulations of uniaxial tensile deformation of DP600 steel were carried out using a modified Rousselier ductile damage model at different strain rates ranging from 0.1 to 100 $s^{-1}$. Since the original Rousselier model does not consider any secondary void nucleation or coalescence criteria, it was modified by including a strain-controlled void nucleation function, a coalescence criterion and a void growth acceleration function as the post-coalescence regime identifier. The predicted flow behaviour, the evolution of damage and critical strain and void volume fraction at the onset of coalescence were assessed to evaluate the performance of the proposed model at each strain rate. In addition, X-ray tomography analysis was employed to evaluate the void volume fraction predicted by each void coalescence criterion. The modified Rousselier model showed good agreement with the experimentally determined strain and void volume fraction at the onset of coalescence. Also, it could successfully predict the damage distribution and the final damage geometry of DP600 tensile specimens.

## 1. Introduction

Prediction of damage and failure in engineering materials and structures is a challenging field of research that has gained a lot of attention in both academia and industry. Accurate assessment of structural integrity of sheet metal products by numerical analysis, with regard to the development of new high performance materials, is of great importance since it can contribute to higher design efficiency, and more cost and time effectiveness [1]. Sheet metals can exhibit different forming and failure behaviour depending on the loading conditions such as the strain path and strain rate. Therefore, it is essential to utilize an accurate hardening law, ductile damage model and fracture criterion in numerical simulations to accurately reproduce experimental behaviour.

The use of dual phase (DP) steels is rapidly growing in the automotive industry due to their superior performance in terms of combined ductility, work hardening rate, strength-to-weight ratio and crash resistance. Their microstructure usually consists of 5–30 vol% martensite, responsible for strengthening the material, distributed in a ductile ferrite matrix which accommodates the deformation throughout the forming process [2–4]. Tasan et al. [5] investigated the effect of microstructural properties of a dual phase steel on the localization and damage mechanisms for different strain paths. Besides conventional low strain rate forming processes used to deform these steels, such as stamping and hydroforming, there is an increasing interest in the automotive industry to utilize high strain rate deformation processes, such as electromagnetic or electrohydraulic forming, which can result in significantly higher formability [6,7]. Experimental research has shown remarkable improvement in the formability of DP500, DP600, DP780 and DP980 steel sheets that were subjected to electrohydraulic deformation process [7,8]. In addition, Amirmaleki et al. [9] used the representative volume element (RVE) method to model the flow behaviour of DP500 and bainite-aided DP600 steels. Accordingly,

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**Nomenclature**

| | |
|---|---|
| $\alpha_t$, $\beta_t$ | Thomason coalescence model coefficients |
| $\beta$ | scalar damage variable |
| $\chi$ | void space Ratio |
| $\delta$ | multiplicative void growth acceleration factor |
| $\dot{\varepsilon}$ | strain rate |
| $\dot{\varepsilon}_0$ | reference strain rate |
| $\eta$ | function of void distribution |
| $\gamma$ | cell geometry related coefficient |
| $\lambda$ | plastic multiplier in the normality rule |
| $\sigma$ | true stress |
| $\sigma_I$ | maximum principal stress |
| $\sigma_m$ | hydrostatic stress |
| $\sigma_{eq}$ | equivalent stress |
| $\varepsilon$ | true strain |
| $\varepsilon_c$ | critical strain at the onset of coalescence |
| $\varepsilon_f$ | fracture strain |
| $\varepsilon_N$ | mean strain at void nucleation |
| $\varepsilon_p$ | equivalent plastic strain |
| $\varepsilon_{I,II,III}$ | principal plastic strains |
| $\vartheta$ | current void distribution |
| $\vartheta_0$ | initial void distribution |
| $C_{1\ldots n}$ | fitting parameters of hardening functions |
| $D$, $\sigma_1$ | adjustable Rousselier damage model parameters |
| $D_0^P$ | arbitrary upper bound strain-rate |
| $f$ | current void volume fraction |
| $f^*$ | effective void volume fraction |
| $f_0$ | initial void volume fraction |
| $f_c$ | critical void volume fraction at the onset of coalescence |
| $f_f$ | void volume fraction at failure |
| $f_N$ | volume fraction of void nucleating particles |
| $f_u^*$ | final effective void volume fraction at final damage |
| $H_0$ | initial height of the unit cell |
| $n$ | strain hardening exponent |
| $R$ | hardening curve of material |
| $r$ | radius of the void |
| $R_0$ | initial radius of the unit cell |
| $S_N$ | standard deviation |
| $W$ | void aspect ratio |
| CN | cluster nucleation |
| SCVN | strain controlled void nucleation |

developing a complete micromechanical damage model based on precisely calibrated constitutive equations, void nucleation and void growth functions, and a void coalescence criterion would help to predict the hardening, instability and damage behaviour of investigated DP steel in a wide range of strain rates, from quasi-static conditions to high strain rates.

A micromechanical approach to ductile failure relates the damage of most engineering alloys to nucleation of microvoids during the deformation because of crack initiation at second phase particles or at the interface between hard particles and the ductile matrix. As the deformation progresses, voids grow as a result of increasing strain and consequently, the load bearing capacity of the material progressively decreases until coalescence of cavities leads to complete failure [10,11]. McClintock [12], and Rice and Tracey [13] were among the first researchers to describe the growth of a cylindrical or spherical void in an infinite deforming ductile material with no strain hardening. In these early models, no interaction between voids and the coalescence process was considered, and failure was simply linked to the critical value of the void radius. Later, various thermodynamically consistent models, based on porous material plasticity, were proposed and the best known are those developed by Gurson [14], Gurson-Tvergaard-Needleman (GTN) [15,16], Rousselier [17,18] and Lemaitre [19]. GTN is perhaps the most widely-used model to evaluate the forming and failure behaviour of different materials in different forming processes, and it can predict void initiation, growth and coalescence using a void growth acceleration function. Chen and Dong [20] employed a modified GTN model accompanied by Hill's quadratic yield criterion to evaluate the damage in plane strain tension and deep drawing. Butcher et al. [21] used this model to predict the onset of fracture in tube hydroforming of DP600. Ramazani et al. [2] derived the flow limit curve of a DP steel deformed in a cross-shaped die. However, the original Gurson model and the version modified by Tvergaard and Needleman are not able to predict the damage for zero or negative stress triaxiality ($\sigma_m/\sigma_{eq}$) values, e.g. in pure shear deformation. Some researchers have proposed improved versions of GTN damage model in order to overcome this deficiency [22–24], although Bao and Wierzbicki acknowledged that it is difficult to define a damage model that is capable of predicting the damage behaviour of a material for different stress triaxialities [25].

The Rousselier model has also been used in several studies to model the deformation and damage behaviour of materials in terms of void evolution. Besson et al. [26] used the Rousselier function to model crack growth and formation of cup-cone fracture surfaces; Poussard et al. [27] employed it to simulate the damage in smooth tensile and compact tension specimens. Samal and Shad [28] predicted the fracture resistance behaviour of cracked fuel pin specimens using this model; and Tu et al. [29] simulated the fracture and crack propagation in steel electron-beam-welded joints and aluminium laser-welded joints. Despite some similarities between the GTN model and the Rousselier model, there are some important differences between them. In case of very low, zero or negative stress triaxiality, the Rousselier model allows damage to initialize and grow whereas in GTN, no damage growth can be generated. In addition, the GTN model was developed based on the growth of a spherical or cylindrical shaped void in the material, whereas Rousselier did not establish his model based on any particular void shape. Therefore, it is possible for the Rousselier model to capture the transition from a flat to oblique fracture surface without any additional term or further modifications [30,31]. To identify material parameters that are needed for calibrating the Rousselier damage model, Springmann et al. [32] proposed an identification algorithm based on a combination of a least squared minimization procedure and a non-linear gradient based optimization method. They showed that their proposed approach was successful when optimizing one material parameter, but the global minimum of the objective function could not be easily obtained when two or more material parameters were considered as variables. However, the original Rousselier model does not include any void nucleation function, or coalescence criterion that would trigger coalescence based on a critical void volume fraction [30]. Recently, Zanganeh et al. [33] proposed an approach to couple the Rousselier model and a coalescence criterion and evaluated the model for different positive triaxiality levels using notched specimens in uniaxial