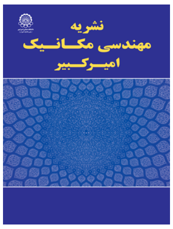

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Micromechanical Damage Model for Plasticity of Metals to Predict Failure under Shear Loads

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ABSTRACT: The present work deals with the Gurson-Tvergaard-Needleman micromechanics based damage model to add the ability to predict damage under shear loads and use it in modeling damage and failure under shear dominated loading conditions. In the development of the Gurson-Tvergaard-Needleman model, since different damages have different physical concepts and attenuation effects, so an independent shear damage parameter was presented as a function of an equivalent plastic strain of the matrix. The modified Gurson-Tvergaard-Needleman damage model was implemented by developing a code in the Abaqus software. To use the modified Gurson-Tvergaard-Needleman model, 16 input parameters of the model were determined for the material under study. After modifying the model, developing the code, and determining the input parameters, it was first tested on a single element. The results of the developed model showed complete agreement with the results of the basic Gurson-Tvergaard-Needleman model and analytical solutions under tensile and shear loads, respectively. Finally, the developed model was tested in shear loading on the shear specimen. It was observed that the modified model eliminates the weakness of the base Gurson-Tvergaard-Needleman model and well predicts the occurrence of damage and weakening of the mechanical properties of the material under the prevailing shear conditions.

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1. INTRODUCTION

Since the introduction of the Gurson-Tvergaard-Needleman (GTN) damage model by T. Vergard and Needelman, many studies have been carried out on failure analysis of various materials using the capabilities of this model.

Despite the popularity of the GTN model and its success in predicting failure under moderate to high stress triaxiality conditions, this model has obvious limitations under shear loading conditions where low stress triaxiality exists (Nahshon and Hutchinson [1]; Xue [2]; Nielsen & T. Vergard [3]; Achuri et al. [4]; Cao et al [5]; Malcher et al. [6]; Zhou et al. [7], Jiang et al. [8]). This major drawback is more pronounced in the case of pure shear, where the stress triaxiality is close to zero because the GTN model does not predict voids growth and damage accumulation under shear conditions. In recent years, some modifications have been made to the GTN model by various researchers to eliminate this limitation, taking into account the damage caused by the shear effects. Xue [2] introduced a separate internal damage variable that differs from the void volume fraction damage and extends the GTN model to include damage due to the voids shearing mechanism. Nahshon and Hutchinson [1] introduced damage accumulation due to the shear mechanism by introducing a phenomenological damage relationship in the GTN model. Although these modifications have made some improvements to the GTN model, their disadvantages cannot be ignored. It can be seen that these modifications lead to excessive prediction of volume change and also shear damage may have an additional contribution to the volumetric part of the plastic strain.

The above-mentioned weaknesses are motivations for the development of new models from the conventional GTN model to improve its capabilities. In the present study, with the same motive, the GTN model is modified and its capability is developed for conditions where shear loading is predominant. The modified model will be used to simulate the damage behavior of material through the development of VUMAT code in Abacus software.

2. THE GTN MODEL AND ITS MODIFICATIONS

As one of the first micromechanical models, Gurson [9] proposed his model for the analysis of damage and failure using the upper bound theory of plasticity. The Gurson model yield function with respect to isotropic softening behavior is expressed as follows:

$$\Phi(p,q,\sigma_Y,f)=\left(\frac{q}{\sigma_Y}\right)^2+2f\cosh\left(-\frac{3}{2}\frac{p}{\sigma_Y}\right)-(1+f^2) \tag{1}$$

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where, f , p and σ_Y represent the voids volume fraction, the hydrostatic pressure, and the law of isotropic hardening respectively. Chu and Needleman [10] proposed a relationship for void nucleation, which was later used by T. Vergard and Needleman [11] in the Gurson model. The void nucleation mechanism that results from the failure of impurities within the matrix material and/or the separation of impurities (or secondary phase particles) from the surrounding matrix can be controlled by plastic strain or hydrostatic pressure. The definition of voids nucleation based on plastic strain is as follows:

$$\dot{f}_n = \frac{f_N}{S_N\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\bar{\varepsilon}_m^p - \varepsilon_N}{S_N}\right)\right]\dot{\bar{\varepsilon}}_m^p \tag{2}$$

The change in the volume fraction of voids is due to the nucleation of new voids and the growth of existing voids.

$$\dot{f} = \dot{f}_n + \dot{f}_g \tag{3}$$

With some corrections, the Gurson model yield function has changed to the new relation and is known as the Gurson-Tvergaard-Needlman or GTN damage model.

$$\Phi(p,q,\sigma_Y,f) = (\frac{q}{\sigma_Y})^2 + 2q_1 f^{*}\cosh(-\frac{3}{2}\frac{q_2 p}{\sigma_Y}) - (1 + q_3 f^{*2}) \tag{4}$$

Nahshon and Hutchinson [1] added an expression to the evolution law of the voids volume fraction to account for the amount of shear damage due to the shear effect in the GTN model. Therefore, the relationship between damage evolution became a sum of three relationships for voids nucleation, voids growth, and shear damage.

$$\dot{f} = \dot{f}_n + \dot{f}_g + \dot{f}_s \tag{5}$$

$$\dot{f}_s = k_\omega f\,\omega(\boldsymbol{\sigma}_{ij})\frac{\mathbf{S}_{ij}\dot{\boldsymbol{\varepsilon}}_{ij}^p}{q} \tag{6}$$

In the proposed function of Nahshon and Hutchinson for shear damage, k_ω has been introduced as a new material parameter to regulate the growth rate of damage in pure shear conditions and $\omega(\boldsymbol{\sigma})$ is a function of the stress state used by Nahshon and Hutchinson. This function varies between the values of zero and one, where zero is for the axial stress state and one for the shear stress conditions.

$$\omega(\boldsymbol{\sigma}) = 1 - \xi^2 = 1 - (\frac{27J_3}{2q^3})^2 \tag{7}$$

3. RESULTS AND DISCUSSION

Fig. 1 shows the force-displacement curve extracted from the finite element simulation along with the experimental force-displacement curve for the shear specimen. As it turns out, there is a good agreement between the experimental results and the simulation results performed with the developed GTN model. Fig. 1 exhibits that the modified GTN model was able to well predict the amount of maximum force, displacement at the fracture point, as well as the process of softening and weakening of material properties due to the effects of shear damage that occurs in the tensile test of the shear specimen. In contrast, this figure illustrates the weakness of the base GTN model in incorporating the effects of shear damage. As it turns out, there is a remarkable

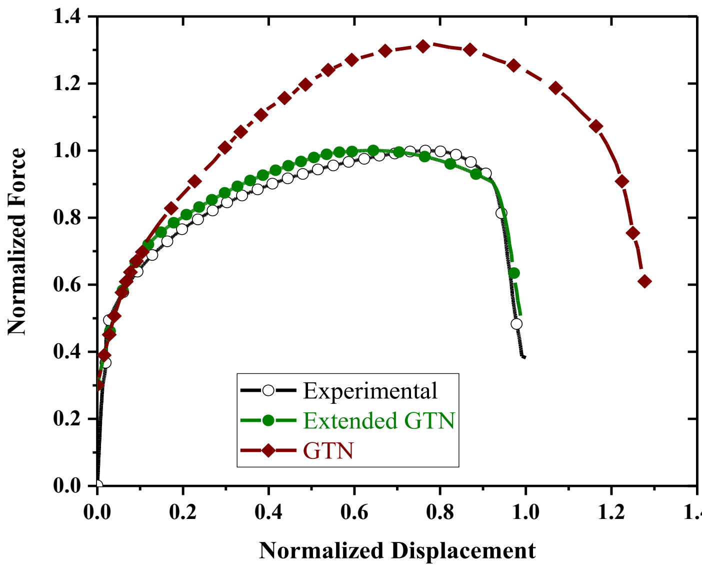

Fig. 1. Experimental and numerical force-displacement curves for shear specimen

difference between the experimental force-displacement curve and the curve predicted by the base GTN model. The damage and failure mechanisms in the GTN model, which include nucleation, growth, and coalescence, operate under tensile stress conditions. In fact, in the simulation of the shear specimen with the GTN model, due to the inability to calculate the shear damage and its involvement in the plastic behavior, the material is constantly hardened in the absence of damage, and its strength increases. This is shown by the increase of force in Fig. 1. This increase in force continues until the elements in the shear deformation zone rotate and align in the direction of tension, therefore providing the conditions for nucleation, growth, and coalescence of voids.

After the start of this stage, the accumulation of damage due to the voids volume fraction continues until it reaches the critical value. By reaching the critical value, it leads to the separation and removal of the elements and a drop in force in the simulation. In fact, in the simulation of the shear specimen with the GTN model, the final failure occurs by damage accumulation under tension. This is contrary to the experimental tests in terms of failure mechanism and occurs with a long delay in terms of displacement.

4. CONCLUSION

In the present study, an attempt was made to develop the micromechanics based GTN damage model to add predictability and calculation of damage under shear loads, so it can be used to model damage and failure in shear specimens where shear loads and shear damage are dominant. By adopting a phenomenological approach and assuming that shear damage is controlled by the equivalent plastic strain of matrix and stress state, a relation for shear damage was proposed. The proposed shear damage parameter was entered in the GTN model with the Lemaitre damage concept and coupled with the material behavior.

In order to use the GTN model developed in VUMAT format for damage analysis, 16 input parameters of the developed model were determined for the material under study. In order to validate the accuracy of the determined parameters, the uniaxial tensile test using these values was simulated and the extracted force-displacement curve was compared with the experimental one, which showed a very good agreement with an error of less than 5%.

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