NUMERICAL PREDICTIONS AND EXPERIMENTAL VALIDATIONS OF DUCTILE DAMAGE EVOLUTION IN SHEET METAL FORMING PROCESSES

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ABSTRACT Prediction of forming limit in sheet metal forming is among the most important challenges confronting researchers. In this paper, a fully coupled elastic-plastic-damage model has been developed and implemented into an explicit code. Due to the adoption of the plane stress and finite strain theories, model can predict deformation and damage of parts quickly and accurately. Also, damage initiation, propagation, and fracture in some operations are predicted and validated with experiments. It is concluded that finite strain combined with continuum damage mechanics can be used as a quick tool to predict ductile damage, fracture, and forming limits in sheet metal forming processes.

KEY WORDS ductile damage, finite strain, fracture, sheet metal forming

I. INTRODUCTION

Sheet metal forming processes are among the most widely used operations in manufacturing industries. With these processes, thin-walled products of complicated shapes in various domains, for example, automotive panels can be made. The main goal of production industries is to make excellent parts in fewer forming operations. Hence, prediction of the forming limits can play a fundamental role in reduction of costly trials. In forming operations, damage and fracture may be observed on the work piece. The damage of materials is a progressive physical process by which they may break. The continuum damage mechanics (CDM) is the study, through mechanical variables, of the mechanisms involved in this deterioration when materials subjected to loading. During a forming process, the change of micro-structure of material changes causes a decrease in its strength[1,2]. From a physical point of view, damage is always related to plastic or irreversible strains and more generally to strain dissipation either on the mesoscale, the scale of the representative volume element (RVE) or on the microscale, the scale of the discontinuities[3].

The study of large deformations in metals has revealed the phenomenon of initiation and growth of microvoids, cavities and microcracks in the process of ductile plastic damage. As experimentally verified for many materials by Lemaitre (1984)[4], the energy dissipation, growth of voids and microcracks, which accompany large plastic flow, has a dominant effect on ductile damage similar to material failure. This fact suggests that the prediction of rupture as well as material properties requires considering a coupling between plastic flow and damage evolution in the constitutive equations.

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Over the last two decades, damage mechanics theory has been developed and applied successfully to study a wide range of engineering problems of practical importance such as predictions of plastic instability and ductile fracture in sheet metal forming processes\[5–14\]. In these researches, authors have used three dimensional stress algorithms and solid or brick elements in their simulations even for thin sheets which are very time consuming. Meanwhile their works are based on small strain elastoplastic theory which is not appropriate and recommended for sheet metal forming operations with large deformations or rotations. Therefore, it seems that a cost effective ductile damage model, particularly developed for sheet metals with large deformation is still essentially needed.

In this paper, a fully coupled elastic-plastic-damage model is proposed and implemented into an explicit code. In this model, Simo et al.’s return mapping algorithm for plane stress elastoplasticity\[15,16\] is applied. De Souza Neto and Andrade Pires et al.’s\[17,18\] approaches which are developed based on Lemaitre’s damage growth and defined for finitely deforming ductile materials, are also considered in the present study. Based on the fact that when load reversal is absent or negligible, the kinematics hardening in the original Lemaitre’s model can be disregarded, and only isotropic hardening is taken into account. It should be mentioned that the proposed plane stress version of Lemaitre’s model needs only one damage parameter as compared with other damage models such as Gurson’s model.

In the following, a constitutive integration algorithm is deduced in which the return mapping procedure under any stress state is degenerated to the solution of a single non-linear equation. Due to using the plane stress algorithm which is valid for thin sheet metals and finite strain theory, the model can quickly and accurately predict both deformation and damage behaviour of various sheet metal parts. For evaluation of the proposed model, damage initiation, propagation and ductile fracture behaviour of sheet metals in some sheet metal forming processes such as a notched specimen under tension, tube hydro-forming and bore-expanding operations are simulated and verified by experimental results. Meanwhile, to further substantiate the effectiveness of the current model, Erichsen’s cupped test is numerically simulated by the model to predict forming limit diagram (FLD) and empirical tests are carried out to validate the numerical results. Hence, finite strain theory combined with continuum damage mechanics can be used as a robust and rapid tool to predict ductile damage, fracture and limiting of forming in various sheet metal forming operations.

II. CONTINUUM DAMAGE MECHANICS MODEL

The plane stress constraint may be systematically introduced as follows. Let \(V^S\) be the vector space of symmetric rank-2 stress tensors; thus, \(\dim V^S = 6\). The plane stress subspace \(V^P\) is obtained from three constraints as

\[
V^P := \{ \sigma \in V^S \mid \sigma_{13} = \sigma_{23} = \sigma_{33} = 0 \}
\]

Similarly, the deviator subspace \(V^D\) is defined by three constraints:

\[
V^D := \{ s \in V^S \mid s_{13} = s_{23} = 0, s_{kk} = 0 \}
\]

Hence, \(\dim V^P = \dim V^D = 3\). Since both \(V^P\) and \(V^D\) are isomorphic to \(R^3\), it would be more convenient to introduce vector notation instead of tensor notation, i.e., to express \(\sigma \in V^P\) and \(s \in V^D\) as

\[
\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{22} & \sigma_{12} \end{bmatrix}^T, \quad s = \begin{bmatrix} s_{11} & s_{22} & s_{12} \end{bmatrix}^T
\]

Therefore, the mapping \(\mathbf{P} : V^P \rightarrow V^D\) connecting the constrained stress vector \(\sigma\) and its deviator \(s\) plays a crucial role. In matrix notation it is

\[
\mathbf{s} = \mathbf{P}\sigma, \quad \mathbf{P} = \frac{1}{3} \begin{bmatrix} 2 & -1 & 0 \\ -1 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}
\]

The component \(s_{33}\) is none-zero but does not explicitly appears in Eq.(4). Finally the components of the strain tensors are shown in vector forms as

\[
\varepsilon = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{22} & 2\varepsilon_{12} \end{bmatrix}^T, \quad \varepsilon^P = \begin{bmatrix} \varepsilon_{11}^P & \varepsilon_{22}^P & 2\varepsilon_{12}^P \end{bmatrix}^T, \quad \varepsilon = \varepsilon^e + \varepsilon^p
\]

\(\cdot\)

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