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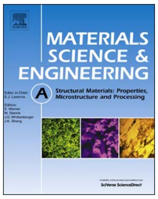

Micromechanics-based damage model for failure prediction in cold forming

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ABSTRACT

The purpose of this study was to develop a micromechanics-based damage (micro-damage) model that was concerned with the evolution of micro-voids for failure prediction in cold forming. Typical stainless steel SS316L was selected as the specimen material, and the nonlinear isotropic hardening rule was extended to describe the large deformation of the specimen undergoing cold forming. A micro-focus high-resolution X-ray computed tomography (CT) system was employed to trace and measure the micro-voids inside the specimen directly. Three-dimensional (3D) representative volume element (RVE) models with different sizes and spatial locations were reconstructed from the processed CT images of the specimen, and the average size and volume fraction of micro-voids (VFMV) for the specimen were determined via statistical analysis. Subsequently, the micro-damage model was compiled as a user-defined material subroutine into the finite element (FE) package ABAQUS. The stress-strain responses and damage evolutions of SS316L specimens under tensile and compressive deformations at different strain rates were predicted and further verified experimentally. It was concluded that the proposed micro-damage model is convincing for failure prediction in cold forming of the SS316L material.

1. Introduction

The identification of damage initiation and evolution is always a key concern in the metal forming process [1]. Classical damage theory is based on the continuum mechanics-based thermodynamics framework initiated by Kachanov, Lemaitre and Chaboche [2–5], which is known as continuum damage mechanics (CDM). Following on the basic concept of effective stress, researchers have paid much attention to the application of the CDM approach in different material forming or loading conditions. Wang [6] developed a unified nonlinear damage evolution rule for ductile materials. By using two damage state variables, Chaboche et al. [7] proposed a modified CDM model to describe the plastic compressibility in ductile damage. Pires et al. [8] improved the original CDM model by incorporating the micro-crack closure effect to predict the damage growth and fracture initiation in ductile materials. Soyarslan and Tekkaya [9] developed a modified CDM model coupled with multiplicative finite plasticity to study the propagation of inner defects in forward extrusion. However, although this phenomenological CDM model saves computational time, it ignores the physical details, e.g., micro-defects, of the material [10–12].

Thus, another approach, the micromechanics-based damage (micro-damage) model, which considers the effects of void initiation and evolution, was developed and brought to the front as a popular research topic. This approach was originally developed by Gurson [13] and known as the GTN model [13–15]. In the GTN model, ductile fracture occurs through the void nucleation, growth, and coalescence. The void coalescence is the final stage in the fracture of ductile materials. It can be triggered by localized plastic deformation inside the inter-void ligament between neighbouring voids and can be modelled by accelerating void growth at a critical void volume fraction. Needleman and Tvergaard [14] improved the GTN model by taking into account the void evolution and material strain hardening. In order to describe the ductile materials with irregular-shaped voids, Gologanu and Leblond [16] extended the GTN model based on an “expansion” velocity field condition. By considering the void shape, void location, strain hardening and stress triaxiality, Pardoen and Hutchinson [17] enhanced the GTN model to establish the criterion of void coalescence.

In the application of the micro-damage model for damage prediction [11,18], the identification of micro-void initiation and growth is of great importance. For micro-voids detection, destructive methods are used commonly to measure its interior distribution. In addition, the VFMV is always evaluated by quantitative metallographic analysis or microscopic examinations [18–21]. However, such testing procedures are destructive, and it is unimaginably difficult to locate the cross-sections and obtain other useful information from numerous micro-voids accurately. In view of this, X-ray CT is an ideal alternative technique that avoids material destruction and allows for superior

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Nomenclature

$\mathbf{F}$	Deformation gradient tensor
$\mathbf{R}$	Rotation tensor with orthogonality
$\mathbf{h}$	Hencky's logarithmic strain
$\mathbf{h}^e$, $\mathbf{h}^p$	Elastic and plastic strain tensors respectively
$\mathbf{D}$	Stretching tensor
$\mathbf{D}^e$, $\mathbf{D}^p$	Elastic and plastic stretching tensors respectively
E	Elastic modulus
ν	Poisson's ratio
$\boldsymbol{\tau}$	Kirchhoff stress tensor
$\mathbf{D}^{p'}$	Deviatoric stress tensor
$\mathbf{D}^{p(m)}$	Hydrostatic stress tensor
f	Volume fraction of micro-voids (VFMV)
ρ	Specific density of the material
p	Accumulated plastic strain
$\dot{p}$	Accumulated plastic strain rate
n, K	Material viscosity constants
$\langle\rangle$	McCauley operator
$\mathbf{N}$	Unit normal vector of the yield surface
F_y	Yield surface
s_i, i=1, 2	Damage parameters
Q	Isotropic hardening deformation resistance
R^{sat}	Saturated stress value
β	Evolution rate of R

image quality of the inner microstructure [22]. It is not only for image capturing and generating external 3D profiles, but also for visualizing internal features of solid objects. Digital volumetric data of the tested specimens can be obtained simultaneously by the high-end data-analysis and visualization software, so as to obtain more reliable information, such as the spatial location, size, compactness, and sphericity, etc., of micro-voids. This enables more accurate calculation of the void volume fraction [23,24]. It is a very powerful tool to realize and support the material microstructure characterization as well as high-resolution micro-interior reverse engineering for various applications such as high-precision engineering, defect detection, composite material science, dimensional metrology and other potential applications [25].

The above phenomenological CDM or micro-damage models are always implemented in finite element (FE) packages for damage prediction of metallic materials. However, the application of the X-ray CT technique for damage parameter identification in the micro-damage model has rarely been studied. Also, most of the mentioned constitutive models coupled with damage were formulated within the small deformation framework, which limited their applications in the large deformation processes of metallic materials with good plasticity [26,27].

Thus, the main objective of this study was to develop a micro-damage model framework for failure prediction in the large deformation of metallic material undergoing cold forming. Typical stainless steel SS316L, which possesses good ductility, high strength and superior corrosion resistance [28], was selected as the specimen material for the X-ray CT scanning and uniaxial tension and compression tests. A micro-focus high-resolution X-ray CT system was employed specially to trace and measure the micro-voids of the specimen directly. In which, the micro-voids inside the material can be modelled precisely and accurately. Furthermore, 3D RVE models with different sizes and spatial locations were reconstructed and the average size and VFMV for the specimen were determined via statistical analysis. Subsequently, the aforesaid micro-damage model was compiled as a user-defined subroutine into ABAQUS. The stress-strain responses and damage evolution in cold forming of SS316L were predicted and further verified experimentally.

2. Micromechanics-based damage model

In this section, a micromechanics-based damage model describing the large deformation behaviour of metallic material was presented. The specific constitutive equations of the micro-damage model based on hypo-elastic relations were derived [17,29]. In order to describe the elasto-plastic behaviour of metallic materials, the additive decomposition of the Hencky's logarithmic strain $\mathbf{h}$ is defined as [30]

$$\boldsymbol{h} = \boldsymbol{h}^e + \boldsymbol{h}^p, \tag{1}$$

where $\boldsymbol{h}^e$ and $\boldsymbol{h}^p$ are the elastic and plastic strain tensors respectively.

For large deformation conditions, the logarithmic strain $\mathbf{h}$ can be replaced by stretching tensor $\mathbf{D}$ as

$$\mathbf{D} = \mathbf{D}^e + \mathbf{D}^p, \tag{2}$$

where $\mathbf{D}^e$ and $\mathbf{D}^p$ are the elastic and plastic stretching tensors, respectively. Further, the elastic strain tensor $\boldsymbol{h}^e$ can be assumed as a state variable to formulate the constitutive equations, and it conforms to the following expression

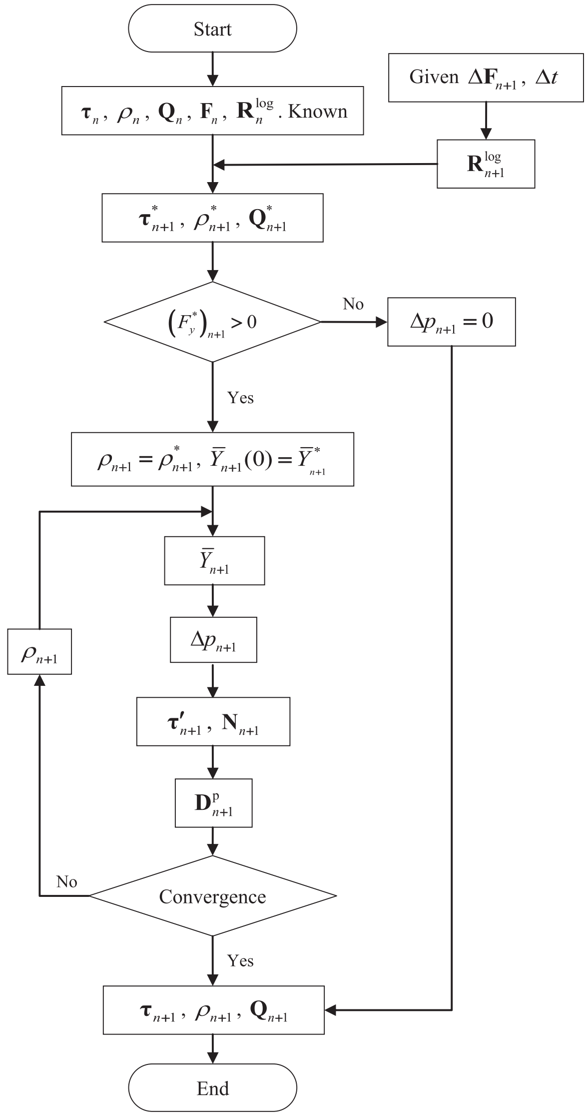

Fig. 1. Flow chart of the stress integration algorithm of UMAT subroutine.