Engineering Fracture Mechanics 149 (2015) 89–110

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

# Computational investigation of multi-axial damage modeling for porous sintered metals with experimental verification

Songyun Ma [a], Huang Yuan [b,*]

[a] Institute of Materials Research, Helmholtz Research Center Geesathacht, Germany
[b] School of Aerospace Engineering, Tsinghua University, Beijing, China

ARTICLE INFO

*Article history:*
Received 7 January 2015
Received in revised form 27 September 2015
Accepted 28 September 2015

*Keywords:*
Sintered metals
Damage evolution
Continuum damage model
Elastic damage
Plastic damage
Stress triaxiality

ABSTRACT

The experimental investigation shows that the damage process in sintered metals starts in almost zero loading and can be divided into three stages: the elastic stage, the secondary stage and finally the tertiary stage. A phenomenological continuum damage model is introduced to predict the inelastic behavior of the sintered material and the damage process. The numerical implicit integration algorithm is developed and implemented into ABAQUS. The proposed damaged model is computationally and experimentally verified under multi-axial loading conditions. It is confirmed that the proposed damage model is able to properly describe the mechanical behavior and the damage evolution under most different loading configurations.

## 1. Introduction

With development of powder metallurgy (PM) technology, sintered metals have been increasingly applied to high performance parts with limited fatigue life. In automobile industry, a number of iron-based alloy sintered steels with high mechanical strength were developed for high loaded parts in order to meet requirements of lightweight design and to reduce manufacturing costs [3,36,37]. Therefore, many efforts have been devoted to investigate the damage mechanisms of sintered metals.

The microstructure of sintered metals is complex and heterogeneous due to irregular pores and different alloy distributions. The inherent porosity of the sintered metal is much higher than that in the conventional casting metals (Fig. 1) and varies between 8% and 15% [3], which results in complicated deformation and damage mechanisms. The fraction, size, distribution and morphology of the porosity directly affect mechanical properties of sintered metals. Interconnected pore networks cause strain localizations at relatively small regions between particles, while isolated porosity induces overall deformations [34,46]. Microscopic damage mechanism of sintered metals is investigated in monotonic in-situ tensile tests [10,24]. It is found that micro-cracks always initiate in pores of which the long axis is perpendicular to the tensile direction. These micro-cracks open and/or propagate in the mode I crack direction. Straffelini and Molinari [39] studied the damage evolution in the sintered iron by monitoring both Young's modulus and density changes during tensile testing and argued that damage is developed in two stages: the first stage contains plastic deformations limited to pore edges, and in the second stage the bulk deformations become dominant. Chawla and Deng [13,14,18] showed that the damage developed quickly in early stage of fatigue life under relative high loading amplitude. However, most of published works focus on experimental

---

* Corresponding author.
*E-mail address:* huang.yuan@tsinghua.edu.cn (H. Yuan).

http://dx.doi.org/10.1016/j.engfracmech.2015.09.049
0013-7944/© 2015 Elsevier Ltd. All rights reserved.

## Nomenclature

| | |
|---|---|
| $D$ | damage variable |
| $D_e$ | elastic damage variable |
| $D_p$ | plastic damage variable |
| $D_p^{cr}$ | critical plastic damage |
| $D_e^{sa}$ | saturation of elastic damage |
| $D_f$ | maximum value of damage |
| $E_0$ | elasticity modulus of the undamaged material |
| $\sigma_{ij}$ | stress tensor |
| $\varepsilon_{ij}$ | strain tensor |
| $E_{ijkl}$ | elasticity tensor |
| $\varphi$ | tension–torsion ratio |
| $K$ | coefficient of Ramberg–Osgood model |
| $b$ | parameter of elastic damage model |
| $\Psi$ | tension–torsion factor |
| $e_{ij}$ | deviatoric stress tensor |
| $n$ | strain-hardening exponent of Ramberg–Osgood model |
| $\sigma_H$ | hydrostatic stress |
| $\sigma_{eq}$ | Mises stress |
| $\varepsilon_{eq}$ | equivalent strain |
| $\varepsilon_f$ | tensile fracture strain |
| $\varepsilon_{th}$ | threshold strain |
| $\eta$ | stress triaxiality |
| $\Phi$ | Helmholtz free energy |
| $\Phi_e$ | elastic potential |
| $\Phi_p$ | plastic potential |
| $r$ | plastic hardening variable |
| $\rho$ | Mass density |
| $Y$ | strain energy density release rate |
| $Z$ | material resistance against damage |
| $F_e^D$ | potential function for elastic damage |
| $\lambda_b$ | damage multiplier |
| $Y_0$ | initial material resistance against damage |
| $\psi_p$ | yield function |
| $R(r)$ | plastic strain hardening |
| $S_0$ | damage material parameter |
| $p$ | total accumulative plastic strain |
| $s_{ij}$ | deviatoric stress tensor |
| Superscript “$tr$” | trial value of the variable at the current step |
| Superscript “$t$” | value of the variable at the last step |
| $\varepsilon_{ij}^e$ | elastic strain tensor |
| $\varepsilon_{ij}^p$ | plastic strain tensor |
| $\Delta$ | time increment of the following variable |
| $h$ | plastic hardening tangent modulus |
| $\nu$ | Poisson’s ratio |
| $\alpha$ | plastic damage exponent |
| $\bar{\theta}$ | lode parameter |
| $J_2$ | second invariant of deviatoric stress |
| $J_3$ | third invariant of deviatoric stress |

investigation of damage mechanisms in sintered metals. A quantitative description of the inelastic damage process of sintered metals under complex loading conditions remain a major issue in view of predicting failure of sintered parts in service.

In past decades, various approaches for modeling and predicting the inelastic damage and fracture have been developed and applied to different dense materials. The Gurson–Tvergaard–Needleman (GTN) porous plasticity model, based on the work of Gurson [23], is a micro-mechanical damage model considering effects of micro-void nucleation and growth. Recently, many research efforts have been made to understand the distortion of voids and inter-void linking under shear-dominant loadings. To enhance the prediction capacity of the GTN model, additional terms containing the third stress invariant are incorporated into the porosity evolution law [2,30,43]. Danas and Ponte Castañeda [17] proposed a homogenization-based rate-dependent plasticity model in the framework of finite strain accounting the effect the evolution