MODELLING OF VOID NUCLEATION AND APPLICATION TO THE SIMULATION OF SPALL EXPERIMENTS

FENG-GUO ZHANG
Institute of Applied Physics and Computational Mathematics, Beijing, China

ABSTRACT

Spallation in ductile metals is often dominated by nucleation, growth and coalescence of voids. Previous research clearly shows that the volume density of nucleated voids is closely related to many factors such as grain size, loading condition and the like. In addition, it is confirmed that the nucleation of voids is inhibited by the existing voids with the plastic region around them. Therefore, a new model of dynamic damage is proposed, where the void nucleation equation is coupled with loading condition, porosity and the void growth is described by using a hollow sphere model with micro-inertia effects. The model is used to simulate spall experiments, and simulation results agree well with experimental data.

Keywords: spallation, void nucleation, ductile metal.

1 INTRODUCTION

Damage in materials subjected to dynamic tension is of great importance in many scientific fields. When a target plate is impacted by a flyer plate, compressive shock waves are generated in the two plates. As they encounter the free surface of the target and of the flyer, they reflect back as rarefaction waves. Tensile stress is generated wherever the rarefaction waves interact. As for ductile materials, damage (in the form of voids) will nucleate, grow and coalesce under the higher tensile stress, which can ultimately lead to the formation of a spall layer. Now, many theoretical damage models, both empirical and micro-physical in nature, have been developed to describe and predict phenomenon of spall fracture [1]–[6]. Some of these models are dependent on stress threshold, while others are dependent on strain threshold. Usually the damage level is quantified according to the void volume in the region of fracture for all these models. Up to now, there is no general and satisfactory spall model, and current models are confined in a narrow applicative range and should be further improved [7].

In this paper we focus our attention only on void formation. Recent research on the mechanics of void growth clearly shows that void nucleation may be represented as a bifurcation phenomenon, where a void forms spontaneously followed by highly localized plastic flow around the new void and the growing voids in turn induce relaxation zones in which local stresses decrease, thus decreasing the probability of nucleating voids in these zones [8]. In existing models, nucleation and coalescence are generally dealt with in an empirical fashion [3], [9]–[11]. In recent years, however, renewed attention has been paid to damage processes. In the present work, a new model of dynamic damage is proposed, where the void nucleation equation is coupled with loading condition, porosity and the void growth is described by using a hollow sphere model with micro-inertia effects.

2 VOID GROWTH

As suggested by Czarnota et al. [4] and Jacques et al. [12], the porous ductile material is modelled as an assemblage of hollow spheres where the pairs (a, b) and (A, B) are the current and initial values of the inner and outer radii respectively, and the ratio of b to a is assumed

WIT Transactions on Engineering Sciences, Vol 124, © 2019 WIT Press
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/MC190231

to be identical for all hollow spheres. So, the macroscopic damage can be described by the porosity $\phi = a^3 / b^3$. A single hollow sphere is subjected to the external stress p, where p is a positive hydrostatic tension.

For void early growth ($b < c \le a$), radius c is the elastic–plastic interface), the evolution law of hollow sphere can be written [13] as

$$\begin{aligned}&\rho(1-\phi^{1/3})a\ddot{a} + \rho(1.5 - 2\phi^{1/3} + 0.5\phi^{4/3})\dot{a}^2 \\ &= p/(1-\phi) - \frac{2}{3}Y_0(1 - \ln(Y_0/2G)) - \frac{4}{3}G\cdot\phi,\end{aligned} \tag{1}$$

where Y_0 and G are the yield strength and the shear modulus of the solid respectively. From eqn (1), for an elastic perfectly plastic material, the critical pressure at void nucleation is given by

$$p_c = \frac{2}{3}Y_0(1 + \ln(2G/Y_0)), \tag{2}$$

and radius c is

$$c^3 = (a^3 - A^3)\cdot 2G/Y_0. \tag{3}$$

While the entire sphere has yielded, the evolution law of hollow sphere can be written [2] as

$$\begin{aligned}&\rho(1-\phi^{1/3})a\ddot{a} + \rho(1.5 - 2\phi^{1/3} + 0.5\phi^{4/3})\dot{a}^2 \\ &= p/(1-\phi) - \frac{2}{3}Y_0\ln\frac{1}{\phi} - 2\eta\frac{a\dot{a}}{a_0^2}.\end{aligned} \tag{4}$$

From eqns (1), (3) and (4), we can determine the parameter a_0

$$a_0^3 = a^3(1 - \frac{Y_0}{2G\phi}). \tag{5}$$

3 VOID NUCLEATION

In spallation conditions, where the negative pressures are large, void nucleation tends to be determined more by stress than strain. The volume density of nucleated voids increases with shock pressure and action time of negative pressures increases. At the same time, considering nucleation inhibition, as induced by the growth of already nucleated voids, we propose a new void nucleation rate function as

$$\dot{N} = k\cdot\frac{1}{t_c}\cdot\frac{p - p_c}{p_c}(1 - \phi\cdot 2G/Y_0), \tag{6}$$

where p_c is the critical pressure at void nucleation (see eqn (2)), t_c is the time when the tensile stress p equals to p_c.

4 COMPARISON OF CALCULATION WITH EXPERIMENT

Based on the proposed model, finite element simulations of plate impact tests are carried out to compare with the experiments on OFHC copper. There, the targets (4 mm thick) with the average grain sizes 30, 60, 100, and 200 μm were impacted by the quartz impactor (2 mm) of ～131m/s velocity. Results from the experiments show that void coalescence is observed to dominate the void growth behavior in the 30 and 200 μm samples, whereas void growth is dominated by the growth of isolated voids in 60 and 100 μm samples [14]. Because the present model does not include the process of void coalescence, we choice experiment data of simple with the average grain sizes 60 μm to simulate. Both the calculated results and the experimental data for the free surface velocity profiles are shown in Fig. 1 and damage statistics are listed in Table 1, where the ΔFSV is the free surface velocity difference between the first peak plateau and the first valley, the porosity is the void volume fraction. Comparison between the calculated and experimental results shows that they are in good agreement.

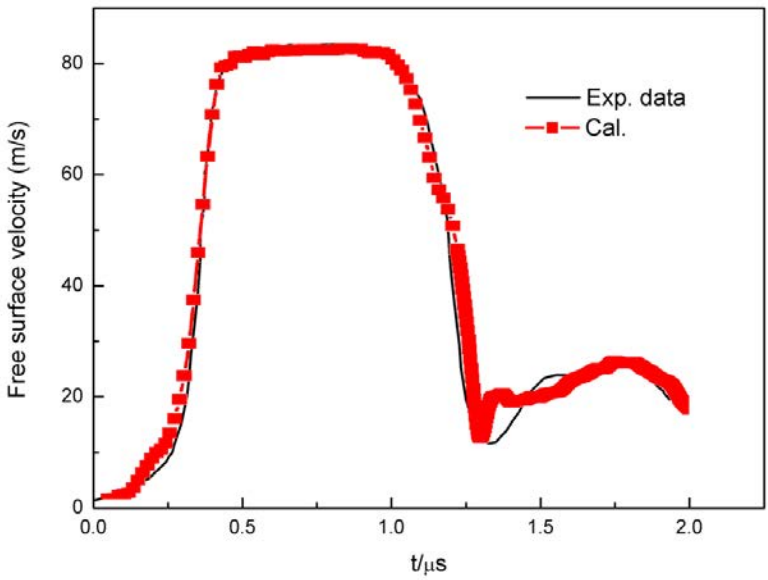

Figure 1: Free surface velocity histories.

Table 1: Damage statistics from optical analysis and numerical results.

	Number of voids ($10^6/cm^3$)	ΔFSV (m/s)	Porosity	Average void diameter (μm)
Exp.	27.15	71	0.166	11.3
Cal.	24.35	68.92	0.107	10.17

5 CONCLUSION

A new void nucleation rate function considering the effects of shock pressure and nucleation inhibition by the growth of already nucleated voids was proposed. The present approach, which includes a new void nucleation rate function and void growth rate in hollow sphere, is used to characterize spall damage in ductile metals subjected to dynamic loading conditions. For simulated plate impact experiment, calculated free surface velocity, number of voids, porosity and average void diameter agree well with experiment data, demonstrating the applicability of the newly developed model.

ACKNOWLEDGEMENTS

This work was supported by the Science Challenge Project (Grant Nos. TZ2018001 and TZ2016001) and the National Natural Science Foundation of China (Grant No. U1530261).

REFERENCES

[1] Gurson, A.L., Continuum theory of ductile rupture by void nucleation and growth. yield criteria and flow rules for porous ductile media. *J. Eng. Mater. Technol.*, **99**(2), 1977.

[2] Johnson, J.N., Dynamic fracture and spallation in ductile solids. *J. Appl. Phys.*, **52**(4) p. 2812, 1981.

[3] Tonks, D.L., Zurek, A.K., Thissell, W.R. & Schwartz, D.S., Modeling incipient copper damage from the tensile Hopkinson bar and gas gun. *Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter*, vol. 706, p. 507, 2003.

[4] Czarnota, C., Jacques, N., Mercier, S. & Molinari, A., Modelling of dynamic ductile fracture and application to the simulation of plate impact tests on tantalum. *J. Mech. Phys. Solids*, **56**(4), p. 1624, 2008.

[5] Seaman, L., Curran, D. & Shockey, D., Computational models for ductile and brittle fracture. *J. Appl. Phys.*, **47**(11), p. 4814, 1976.

[6] Wilkerson, W. & Ramesh, K.T., Unraveling the anomalous grain size dependence of cavitation. *Phys. Rev. Lett.*, **117**(21), p. 215503, 2016.

[7] Chen, X., Asay, J.R., Dwivedi, S.K. & Field, D.P., Spall behavior of aluminum with varying microstructures. *J. Appl. Phys.*, **99**(2), p. 023528, 2006.

[8] Trumel, H., Hild, F., Roy, G., Pellegrini, Y. & Denoual, C., On probabilistic aspects in the dynamic degradation of ductile materials. *J. Mech. Phys. Solids*, **57**(12), p. 1980, 2009.

[9] Bontaz-Carion, J. & Pellegrini, Y.P., X-ray microtomography analysis of dynamic damage in tantalum. *Adv. Engng. Mat.*, **8**(6), p. 480, 2006.

[10] Thomason, P.F., Ductile spallation fracture and the mechanics of void growth and coalescence under shock-loading conditions. *Acta. Mater.*, **47**(13), p. 3633, 1999.

[11] Tonks, D.L., Zurek, A.K. & Thissell, W.R., Coalescence rate model for ductile damage in metales. *J. Phys. IV France*, **110**, p. 893, 2003.

[12] Jacques, N., Mercier, S. & Molinari, A., Void coalescence in a porous solid under dynamic loading conditions. *Int. J. Fract.*, **173**(2), p. 203, 2012.

[13] Carroll, M.M. & Holt, A.C., Static and dynamic pore-collapse relations for ductile porous materials. *J. Appl. Phys.*, **43**(4), p. 1626, 1972.

[14] Escobedo, J.P. et al., Effects of grain size and boundary structure on the dynamic tensile response of copper. *J. Appl. Phys.*, **110**(3), p. 033513, 2011.