Simulation of critical behaviour on damage evolution*

Qi Mei-Lan(祁美兰)[a)b)] and He Hong-Liang(贺红亮)[b)]

[a)] School of Science, Wuhan University of Technology, Wuhan 430070, China

[b)] National Key Laboratory of Shock Wave and Detonation Physics, Institute of Fliud Physics, Mianyang 621900, China

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Based on a damage evolution equation and a critical damage function model, this paper has completed the numerical simulation of ductile spall fracture. The free-surface velocity and damage distribution have been used to determine jointly the physical parameters $D_{\rm l}$ (the critical linking damage), $D_{\rm f}$ (the critical fracturing damage) and k (the softening rate of critical damage function model) of the critical damage function model, which are 0.11, 0.51 and 0.57 respectively. Results indicate that the parameters determined by any of shots could be applicable to the rest of other shots, which is convincing proof for the universal property of critical damage function. In our experiments, the shock pressure is about 1 GPa to 2.5 GPa. For the reason of limited pressure range, there are still some limitations in the methods of present analysis. Moreover, according to the damage evolution characteristic of pure aluminum obtained by experiments, two critical damages are obtained, which are 0.11 and 0.51 respectively. The results are coincident with the experimental ones, which indicate that the critical growth behaviour of damage occurs in the plastic metal under dynamic loading.

Keywords: critical damage, numerical simulation, universal property

PACC: 6250, 6220M, 6120J

1. Introduction

Under dynamic loading, the spallation process is as follows: nucleation of voids at various locations is followed by the growth of voids, and subsequent coalescence of voids resulting in material fracture.

Coalescence is an important process in the damage evolution. Curran *et al.*[1] noted that there were two kinds of linking mechanisms of microcracks: directly connecting, for example, the initial approximate spherical voids grow alone in pure aluminum or copper, but they attach before the location plastic deformation sheet connecting; connecting by the plastic deformation fields around microcracks, for example, Zurek *et al.*[2] found that the larger cracks met together because of appearing the shear fracture band between the cracks. In addition, a number of researchers have drawn the same conclusion about gathering behaviour of microcracks.[3−7] Seppälä *et al.*[8] have simulated the growth and coalescence behaviour of microvoids in copper under dynamic tensile stress by the molecular dynamic simulations. The results show that the plastic deformation field around voids will meet when the space between voids is close to their radius. After that, the void growth rate increases abruptly and the coalescence appears finally.

Based on the damage statistical theory, Feng[9] proposed a damage evolution function,

$$\frac{\partial D}{\partial t} = (1-D)D\frac{(\sigma_{\rm s}^2-\sigma_0^2)}{\frac{4}{3}B\frac{\lambda}{C}}, \tag{1}$$

where D is the damage of matrix, $\sigma_{\rm s}$ is the tensile stress, σ_0 is the threshold stress, B is the bulk modulus, λ is the surface work, and C is the volume sound velocity.

Equation (1) shows the relation between damage and time, but it does not include the gathering progress of voids during the later evolution. When the damage exceeds a certain threshold, strong aggregation process occurs between microvoids, which can cause damage growing rapidly. In order to describe this gathering and catastrophic fracture behaviour, Wang *et al.*[10] have proposed a softening function based on percolation theory,[11] called percolation-softening function,

$$\begin{aligned} & F_{\rm PS}(D) \\ &= 1-\theta(D) \\ &= \begin{cases} 1, & D < D_{\rm l}, \\ 1-k\left(\dfrac{D}{D_{\rm l}}-1\right)^{\beta},\ \beta>0, & D_{\rm f} \geq D \geq D_{\rm l}, \\ 0, & D = D_{\rm f}, \end{cases} \end{aligned} \tag{2}$$

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where D_l is the critical linking damage, D_f is the critical fracturing damage, β is a material parameter related to the percolation characters, which equals 0.4 according to the results of three dimensional (3D) molecular dynamics simulation[12] and percolation theory,[11] k is characterised by the rate of decline (soften) of function $F_{PS}(D)$, namely the rate of stress and strength softens in the damage matrix. In this function, there are three unknown coefficients D_l, D_f and k. Two of them need to be determined by comparing calculated results with experimental ones.

The damage function model and percolation-softening function are used for simulating damage evolution behaviour of pure aluminum in this paper. Firstly, the physical parameters D_l, D_f and k are determined jointly by the free-surface velocity profile and damage distribution statistics of any of shots. Then these parameters are applied to the rest of shots for verifying the universality of the critical damage function model.

2. Free-surface velocity profile and damage distribution

Plate-impact experiments are finished by using a 100-mm-diametre light gas gun. Ultrapure Al rod is commercially provided by Guizhou Aluminum Factory of China. Symmetric impact method is used, i.e., both the flyer and the target are Ultrapure Al. Both the flyer and the sample are 48 mm in diameter. From Shot3 to Shot6, Al samples, approximately 6 mm in thickness, are impacted with 3 mm flyer. For Shot1 and Shot2, Al samples, approximately 4 mm in thickness, are impacted with 2 mm flyer. Figure 1 shows the free-surface velocities of 4 samples with 6 mm thick.

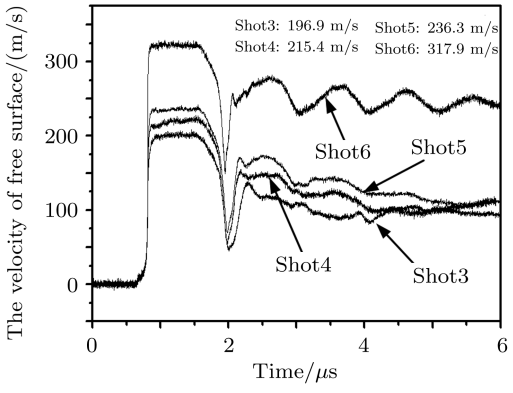


Fig. 1. Free-surface velocity profiles of 4 shots.

Figure 2 shows the metallograph of Shot5 sample. Based on the Schwartz-Saltykov method,[13] Qi and He[14] proposed a statistical method of damage distribution. By this method and metallograph of sample, we can obtain the spatial distribution of damage.



Fig. 2. Shot 5 (6.01 mm, 236.3 m/s impact velocity).

3. Numerical simulation

In the tensile stress region, D and $F_{PS}(D)$ are applied to the stress strain relations of one-dimensional finite-difference codes, which form the constitutive equations with damage,

$$\begin{aligned} P &= P_s[\rho(1-D), E](1-D)\cdot F_{PS}(D), \\ G &= G_s\left[1 - D\frac{15B+20G_s}{9B+8G_s}\right]\cdot F_{PS}(D), \\ Y &= Y_s(1-4D)\cdot F_{PS}(D), \end{aligned} \tag{3}$$

where P is the pressure of matrix with damage, G is the shear modulus of matrix with damage and Y is the yield strength of matrix with damage. The subscript s shows the value of matrix without damage.

There are three unknown coefficients in $F_{PS}(D)$, namely D_l, D_f and k. At first, D_l is given any value and k is given by different types of values for calculation. When the calculated bounce velocity accords perfectly with the experimental result, k can be determined. Then by comparing the calculated and experimental waveform of free-surface velocity profile repeatedly, D_l can be obtained. The preferable D_l and k are used for calculating the damage in camparison with statistical results, the unique D_l and k will be obtained. Finally, according to Eq. (2), when $F_{PS}(D) = 0$, $D = D_f$, namely $1 - k(D_f/D_l - 1)^\beta = 0$, D_f also can be obtained.

In this paper, the free-surface velocity profile and damage distribution of any of shots are calculated. Then by comparing the calculated and experimental results, the correlative parameters of these functions

can be obtained. Figure 3 shows the comparison of free-surface velocity and Fig. 4 shows the comparison of damage distribution. In Fig. 3, the calculated results are more close to the measured ones with the first and third group solutions. But in Fig. 4, the calculated damage distribution fits better with the experimental one with the first group solution than others. If both the free-surface velocity profile and the damage distribution statistics need to be fitted well, the calculated parameters must be more accurate and optimized.

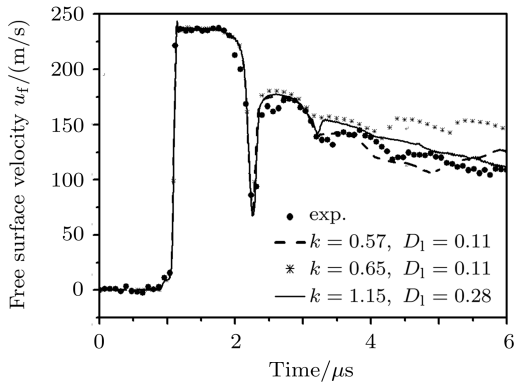


Fig. 3. Experimental and simulated free-surface velocity profile of Shot 5.

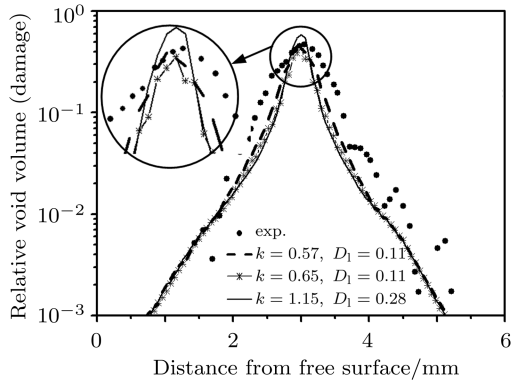


Fig. 4. Experimental and simulated damage distribution of Shot 5.

According to Figs. 3 and 4, the parameters of these functions can be jointly determined, where k equals 0.57 and the critical linking damage D_l equals 0.11, according to Eq. (2), the critical fracturing damage D_f can also be obtained, which is about 0.51. The correlative parameters and calculated results are listed in Table 1.

The parameters D_l, D_f and k determined by Shot5 applied to the other shots for fitting the free-surface velocity profiles and damage distributions. The comparison of measured and calculated results are listed in Fig. 5–11. Results show that whether the free-surface velocity or the damage distribution, the simulated results are approximately in accordance with experimental ones.

Table 1. Calculating parameters and fitting values.

material	C/(m/s)	λ/(kJ/m^2)	σ_0/(GPa)	
Al	5250	0.38	0.1	
B	k	D_0	D_l	D_f
0.4	0.57	5×10^{-5}	0.11	0.51

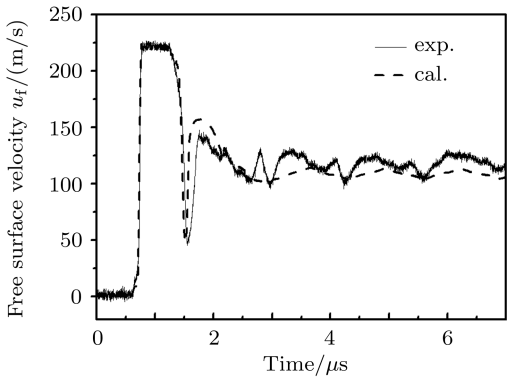


Fig. 5. Experimental and simulated free-surface velocity profile of Shot1 (219.7 m/s impact velocity).

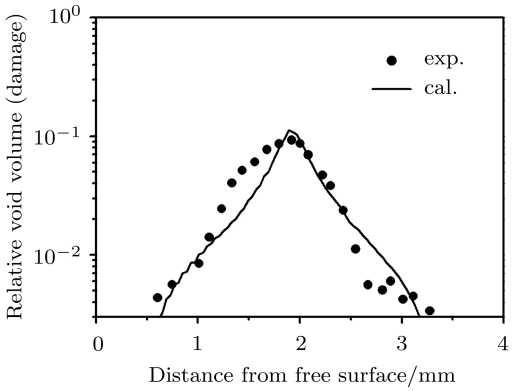


Fig. 6. Experimental and simulated damage distribution of Shot1.

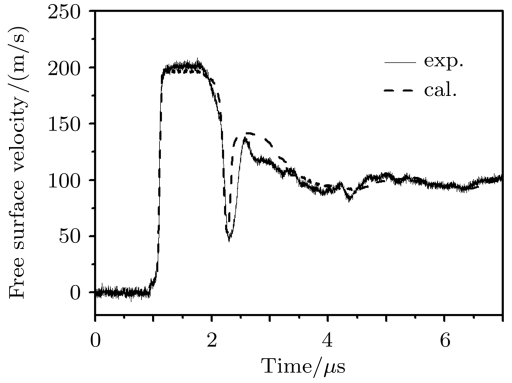


Fig. 7. Experimental and simulated free-surface velocity profile of Shot3.

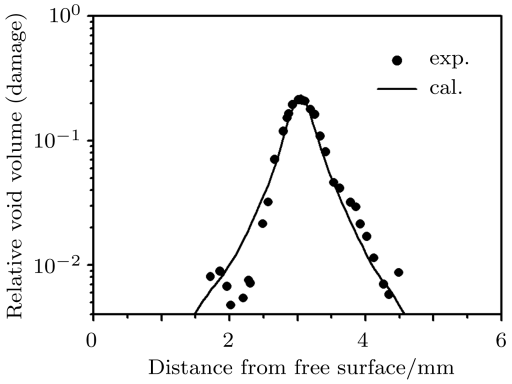


Fig. 8. Experimental and simulated damage distribution of Shot3.

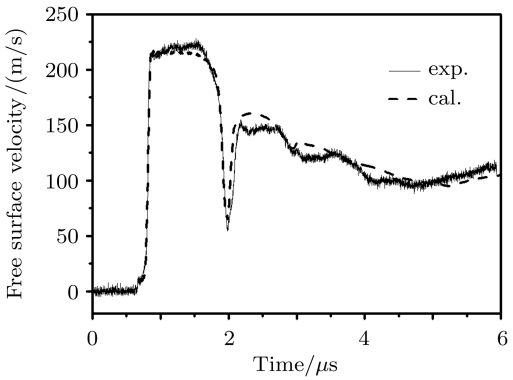


Fig. 9. Experimental and calculated free-surface velocity profile of Shot4.

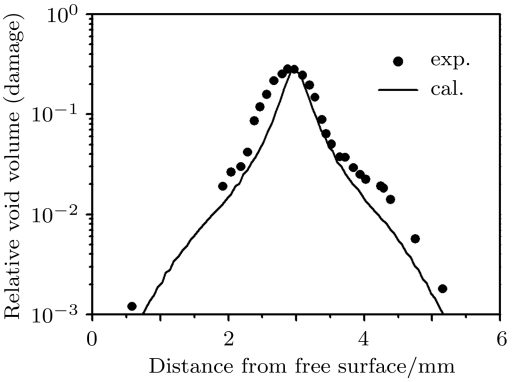


Fig. 10. Experimental and calculated damage distribution of Shot4.

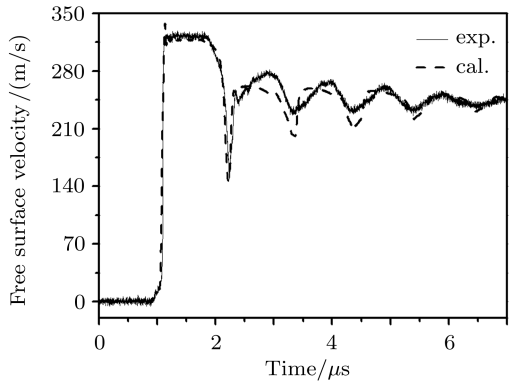


Fig. 11. Experimental and calculated free-surface velocity profile of Shot6 .

4. Results and analysis

In general, 6 shots, which have different impact velocity, tensile strain rate and thickness of the samples, have the same spall behaviour and they can be described well by the same critical damage function model. The results show that the critical damage $D_{\rm l}$ and $D_{\rm f}$ are two constants, which are independent of the loading condition. For Ultrapure Al, the critical linking damage $D_{\rm l}$ and the critical fracturing damage $D_{\rm f}$ jointly determined by the free-surface velocity and damage distribution statistics are 0.11 and 0.51, respectively. When the damage D is less than 0.11, the microvoid grows slowly alone. With the further growth, when D reaches to 0.51, the voids begin to gather and the damage increases rapidly. Once D exceeds 0.51, the matrix material will unstably fracture. This kind of damage evolution rule is consistent with the critical damage behaviour described in Ref. [15]. In Fig. 12, according to the free-surface velocity profiles and damage distribution statistics of samples with incipient spall, two critical damages can be determined, which are about 0.11 and 0.51 and are coincident with the two parameters $D_{\rm l}$ and $D_{\rm f}$ in the critical damage function.

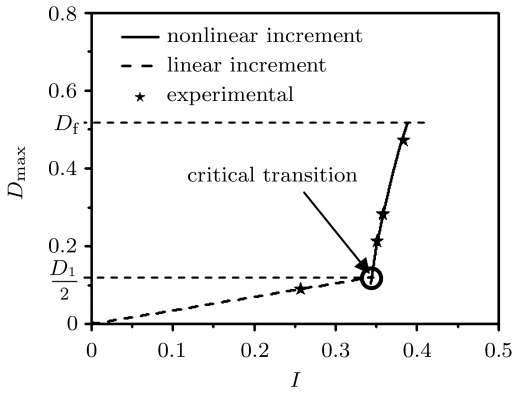


Fig. 12. Two critical damages in damage evolution.

5. Conclusion

Based on the free-surface velocity profile and the damage statistics of 'soft-recovered' samples under the dynamic loading, we can calculate the damage evolution of high purity aluminum. The physical parameters $D_{\rm l}$, $D_{\rm f}$ and k in the critical damage function are determined jointly by the free-surface velocity profile and the damage distribution statistics. Based on the numerical simulation, we also discuss the universal property of the critical damage parameters $D_{\rm l}$ and $D_{\rm f}$. The results indicate that the parameters determined by any of the shots could be applicable to the rest of the other shots. So, the suggestion that the critical damage parameters could be two intrinsic material constants for describing the dynamic tensile fracture is validated further. But our experiments are finished by a one-stage light-gas gun and the shock pressures are about 1 GPa and 2.5 GPa, so the limitations of present analytical methods is existent. Further more, according to the experiments and analysis, two critical damages during the damage evolution are determined, which are coincident with the two parameters of critical damage function. It also shows that the critical growth behaviour of damage is existent in the plastic metal under dynamic loading.

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References

[1] Curran D R, Seaman L and Shockey D A 1987 *Phys. Rep.* **147** 253

[2] Zurek A K, Thissell W R and Trujillo C P 2003 *Los Alamos Science* p111

[3] Bandstra J P and Koss D A 2004 *Mater. Sci. Eng.* A **387–403** 399

[4] Chen J, Chen D Q, Sun J S and Xu Y 2008 *Acta. Phys. Sin.* **57** 6437 (in Chinese)

[5] Li Y J, Xu A G, Yang Q L, Zhang G C and Zhao Y H 2008 *Chin. Phys.* B **17** 940

[6] Bandstra J P, Koss D A, Geltmacher A and Everett R K 2004 *Mater. Sci. Eng.* A **366** 269

[7] Potirniche G P, Hearndon J L, Horstemeyer M F and Ling X W 2005 *Int. J. Plasticity* **22** 921

[8] Seppälä E T, Belak J and Rudd R E 2004 *Phys. Rev. Lett.* **93** 1

[9] Feng J P 1992 *Damage Function Model of Dynamic Ductile Fracture in Metal* (Beijing: Beijing University of Technology) (in Chinese)

[10] Wang Y G, He H L, Wang L L and Jing F Q 2006 *Key. Eng. Mater.* **121** 324

[11] Aharony A and Stauffer D 1998 *Phys. Rev. Lett.* **81** 252

[12] Strachan A, Cagin T and Goddard III W A 2001 *Phys. Rev.* B **63** 1

[13] Saltykov S A 1958 *Stereometric Metallography* 2nd. ed (Moscow: Metallurgizdat) p40

[14] Qi M L and He H L 2008 *Journal Wuhan University of Technology* **30** 23(in Cihnese)

[15] Qi M L, He H L and Yan S L 2007 *Acta. Phys. Sin.* **56** 5965 (in Chinese)