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Dynamic micro-fracture of metals under shock loading by electric gun

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Resume – Des specimens d'aluminium, cuivre OFHC et alliage titane Ti-6Al-4V sont charges par un canon électrique de deux étages. Le procédé de nucléation et croissance de micro-vides dans les specimens est décrit avec le modèle NAG, la relation constitutive et la simulation numérique. Il est prédit que l'intensité de spallation d'aluminium pur monte avec le taux formatique volumique unchargeant plus que $6 \times 10^4 \text{s}^{-1}$.

Abstract – Aluminum, OFHC copper and Ti-6Al-4V specimens have been impacted with the two stage electric gun. The process of nucleation and growth of micro voids in the specimens is well described by the NAG model and related constitutive relation and numerical simulation. It is predicted that the spall strength of pure aluminum goes up with the unloading bulk strain rate greater than $6 \times 10^4 \text{s}^{-1}$.

1. INTRODUCTION

Dynamic fracture in shocked materials is a strain rate dependent process in which micro voids or other flaws occur. Sometimes they lead to damage through nucleation, growth, coalescence and interaction. Meanwhile the flaws affect the macro stress field in the material, so that the dynamic constitutive relation should take fracture effects as well as rate effects into account. The constitutive relation employed here is based on the Gurson's overstress model^[1], while the solid materials (matrixes) are represented by Perzyna's overstress model. Thus, a new yield function considering rate and micro-fracture effects and the related plastic stress-strain relation were obtained. In order to check this model, we have performed the experiments and numerical simulations described in this paper.

A new loading technique, using an electric gun to indirectly drive the secondary impactor, has been developed. It is called the two stage electric gun, but its heavier impactor has a lower velocity than that for the common one stage electric gun. It breaks the restriction that the electric gun can drive high speed (km/s) thin plastic flyers only, and provides low speed (10^2m/s) sub-millimeter thick metallic impactors for elastic-plastic dynamics and dynamic fracture experiments. It should be noted

that this new promising technique is simple, effective and economical^[2].

Furthermore, we improved the 1D reactive hydrodynamic-elastic-plastic code SSS^[6] by incorporating the constitutive relation and the Seaman's NAG model^[10]. Numerical simulations with the code SSS can predict the micro void distributions as well as the material response for metals under planar shock loading. The numerical simulations also reproduce the details of target's free surface velocity histories, especially the important velocity recession process. In contrast to it, the common spall criterion can provide the spall thickness and the target response before spallation only. The reason is that the criterion could be used only for objectively judging the spall process and doesn't interact with the calculated stress or strain field.

The strain rate dependence of a material's dynamic properties is an important aspect of its constitutive relation. Using the considered model it is predicted that the spall strength of pure aluminum will increase rapidly with the strain rate greater than $6 \times 10^4 \text{ s}^{-1}$, where the spall strength is defined as the local tensile stress when the void volume density first reaches 0.09.

2. EXPERIMENTS

The electric gun works by means of an electrically exploding metallic foil. When a pulsed current passes through the bridge foil, a high pressure plasma drives a thin plastic flyer to hit the attenuator in the case of two stage electric gun (Fig.1). Because of its different impedance the impactor previously attached to the other surface of the attenuator can be driven to freely fly as soon as the reflective rarefaction reaches its rear interface with the attenuator. The experimental assembly is illustrated in Fig.1, and the main parameters and their adjustable ranges are as follows:

capacitor bank $36\mu\text{F}$, charging voltage 10–15kV, peak current 361kA, circuit inductance 65nH, Mylar flyer $\Phi 20 \times 0.2$ (mm), velocity 2~6 km/s, glass epoxy attenuator $\Phi 70 \times 3 \sim 8$ (mm), aluminum impactor $\Phi 15 \times 0.7$ (mm), velocity 100~400m/s, flatness of impact $\leq 30\text{ns}$, shock wave in aluminum targets: velocity 5.42–5.62km/s, pressure 0.73–3.03GPa, pulse duration $2.6\mu\text{s}$.

Fig.1 Schematic of two stage electric gun

The experimental data for six shots in the aluminum tests are listed in Tab.1.

Table 1 Experimental Data of Aluminum

Shot No	1	2	3	4	5	6
Impact speed (m/s)	144	267	330	714	761	787
Al impactor thickness (mm)	0.7	0.7	0.7	2.0	2.0	2.0
Al target thickness (mm)	2.0	3.0	3.0	6.0	6.0	6.0

Shots 1–3 were performed with the two stage electric gun mentioned above and for the commercial pure aluminum (type L2). Shots 4–6 were done with explosive loading and for the aluminum alloy (type LY12)^[3].

3. CONSTITUTIVE RELATION AND THE NAG MODEL

Based on the Gurson's model an elastic–viscoplastic constitutive relation considering strain rate and micro fracture effects has been proposed^[4], where the Perzyna's model is employed for the matrix. A yield function then results from this new model,

$$(\sigma / Y_0)^2 ch[4\sqrt{n/(1+5f)}(\dot{E}_a / \dot{\epsilon}_0)^{n/5}(P / X_0)^2] + 2f \cdot ch(3qP / 2Y_0) - 1 - f^2 = 0 \quad (1)$$

where $Y_0 = \sigma_0 [(\dot{E}_a / \dot{\epsilon}_0)^n + 1]$, $X_0 = (2\sigma_0 / 3)[-lnf + (2^{n/2} / n)(\dot{E}_a / \dot{\epsilon}_0)^n(f^{-n} - 1)]$, $q = -(2Y_0 / 3X_0)lnf$, $\dot{E}_a^2 = (2/3)\dot{E}_{ij}\dot{E}_{ij}$, σ : the flow stress, σ_0 : yield strength of matrix material, $\dot{E}_{ij}$: strain rate deviator, $\dot{S}_{ij}$: stress deviator, P : the average stress, f : void volume fraction, $\dot{\epsilon}_0$ and n ($0 < n < 1$) are material constants. The dynamic fracture dependent constitutive relation can be written as follows^[1,4]

$$P / \sigma_0 = \frac{1}{3} \left(\frac{\dot{E}_a}{\dot{\epsilon}_0} \right)^n \left[\omega U_n + \frac{2 - \omega^2}{n+1} \frac{\partial U_n}{\partial \omega} \right] + \frac{1}{3} \left[\omega U_0 + (2 - \omega^2) \frac{\partial U_0}{\partial \omega} \right] \quad (2)$$

$$\frac{\Sigma_e}{\sigma_0} = \left(1 - \frac{\omega^2}{2} \right)^{1/2} \left(\frac{\dot{E}_a}{\dot{\epsilon}_0} \right)^n \left[U_n - \frac{\omega}{n+1} \frac{\partial U_n}{\partial \omega} \right] + \left(1 - \frac{\omega^2}{2} \right)^{1/2} \left[U_0 - \omega \frac{\partial U_0}{\partial \omega} \right] \quad (3)$$

$\omega = 2\dot{E}_{nn} / 3\dot{E}_a$, $\dot{E}_{nn}$: macro bulk strain rate, $\Sigma_e = (3\dot{S}_{ij}\dot{S}_{ij} / 2)^{1/2}$: macro effective stress deviator, $U_0 = U_n|_{n=0}$, and

$$U_n = \frac{\omega}{2} \int_0^\pi \sin \theta d\theta \int_\omega^\infty x^{-2} \left[1 - \frac{\omega^2}{2} - \frac{1}{2} \left(1 - \frac{\omega^2}{2} \right)^{1/2} (1 + 3\cos 2\theta)x + x^2 \right]^{(n+1)/2} dx \quad (4)$$

The nucleation and growth (NAG) model for micro voids and cracks was proposed by Seaman and other workers^[5]. The evolution of nucleation is described by

$$\dot{N} = \begin{cases} \dot{N}_0 \exp[(P - P_{n0}) / P_1] , & P \geq P_{n0} \\ 0, & P \leq P_{n0} \end{cases} \quad (5)$$

$$N(R) = N_0 \exp(-R / R_0) \quad (6)$$

where $\dot{N}$: nucleation rate, N_0 : total void number per cm^3 , $N(R)$: the cumulative void number per cm^3 with radius larger than R , P_1 : adjustable pressure for nucleation. The equation for void growth is

$$\dot{R} / R = (P - P_{g0}) / 4\eta \quad (7)$$

η : material viscosity, $\dot{N}_0$, R_0 , P_1 , P_{n0} , and P_{g0} are material constants, for aluminum L2 or LY12 here, $\dot{N}_0 = 3 \sim 4 \times 10^9 / \text{cm}^3 / \text{sec}$, $R_0 = 1 \sim 3 \times 10^{-4} \text{cm}$, $P_1 = -2.5 \times 10^8 \text{dyne} / \text{cm}^2$, $P_{n0} = -0.2 \sim -1.0 \times 10^9 \text{dyne} / \text{cm}^2$, $P_{g0} = -1 \sim -3 \times 10^9 \text{dyne} / \text{cm}^2$. In addition, the Mie–Gruneisen

equation of state is used for solid and porous materials, also porosity (micro-fracture) dependent shear modulus and yield strength are incorporated into the code SSS^[6], so that better numerical simulations could be performed. Considering the interaction of micro voids and the available experimental data, we set the critical condition for coalescence as $f=0.09$ for spallation.

4. RESULTS AND DISCUSSION

The micrographs of sectioned targets for Shots 1–3 are shown in Fig.2 and indicate the process of nucleation, growth and coalescence of voids with impact speed increasing. Figs 3–4 show the void distributions for Shot 1 and 2, both the measured and calculated ones, where the peak position predicts the spall thickness in Shot 3.

In order to understand the target response to spallation, the free surface velocities were calculated for Shots 4–6, where the experimental data were measured with capacitor transducers. As shown in Tab.2 and Fig.5 for Shot 4–6 the detail of the velocity history is reproduced, especially the velocity recession that characterizes the unloading strain rate and the spall strength. Also the calculation with simple spall criterion (stress gradient and cumulative damage) is shown in Fig.5(b) from which it is concluded that they may provide the right response before spall and the spall thickness only.

Similarly the nucleation and growth of micro voids in OFHC copper and Ti-6Al-4V specimens have been observed (Fig.6, 7). It should be noted that the strain bands occur in the Ti-6Al-4V specimen loaded at lower strain rates and with explosive-driven thicker impactor^[7]. The mechanism and condition for fracture feature transition from strain bands to micro voids are still unknown.

Fig.2 Micrographs of L2 aluminum target

Fig.3 Void distributions for Shot 1

Table.2 Measured spall strength of LY-12 aluminum alloy

Shot No	Impacter velocity $v(\text{km/s})$	Impact pressure $p(\text{GPa})$	Strain rate $\dot{\epsilon}(10^4 \text{s}^{-1})$	Free surface velocity pullback $\Delta u_f(\text{km/s})$	Spall strength $\sigma_s(\text{GPa})$
4	0.714	5.75	1.00	0.14	1.09
5	0.761	6.16	1.07	0.14	1.09
6	0.787	6.39	1.19	0.17	1.20

Finally the strain rate $\dot{\epsilon}$ dependence of spall strength σ_s is explored by the numerical simulation, though the measurement of it is rather difficult. The spall strength shown in Fig.8 means the tensile stress as the local void volume fraction reaches 0.09. The trend of σ_s vs $\dot{\epsilon}$ is something like $\sigma_s \propto \dot{\epsilon}^{1/3}$, just as predicted by fracture mechanics and stress wave models^[7,8], and observed in the laser driven shock wave loading experiments^[7,9]. It is concluded that the model employed in this paper can describe the behavior of strain rate dependence besides the void distributions and the target response to shock loading.

Fig.4 Void distributions for Shot 2

Fig.5 Free surface velocity histories for Shot 4~6

Fig. 6 Micrographs of OFHC copper target

Fig.7 Micrograph of Ti-6Al-4V target

Fig. 8 Calculated strain rate, ϵ , dependence of spall strength, σ_s

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