Effect of grain size and arrangement on dynamic damage evolution of ductile metal*

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Plate-impact experiments have been carried out to examine the effect of grain size and grain arrangement on the damage evolution of ultrapure aluminum. Two groups of samples, "cross-cut" and "longitudinal-cut," are obtained from the rolled aluminum rod along different directions. The peak compressive stress is approximately 1.25 GPa–1.61 GPa, which can cause incipient spall damage that is correlated to the material microstructure. The metallographic analyses of all recovered samples show that nearly all damage nucleates at the grain boundaries, especially those with larger curvature. Moreover, under lower shock stress, the spall strength of the "longitudinal-cut" sample is smaller than that of the "cross-cut" sample, because the different grain sizes and arrangement of the two samples cause different nucleation, growth, and coalescence processes. In this study, the difference in the damage distribution between "longitudinal-cut" and "cross-cut" samples and the causes for this difference under lower shock-loading conditions are also analyzed by both qualitative and semi-quantitative methods. It is very important for these conclusions to establish a reasonable and perfect equation of damage evolution for ductile metals.

Keywords: grain size, grain arrangement, damage evolution, spall strength

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1. Introduction

The strength and performance of materials in extreme environments are of scientific interest because these two parameters determine a wide spectrum of uses in both defense and industrial applications. Understanding the dynamic performance of materials is important, because it helps not only to improve the research and design level of various materials, but also to improve the strength and performance of civil-defense equipment and civilian materials. Spallation experiments are often used as an effective method of studying the dynamic performance of materials in processes such as dynamic damage evolution, which can be induced under high-strain conditions, such as plate impact, laser irradiation or use of highly explosive techniques.[1–3] In a spallation experiment, the damage will nucleate, grow, and coalesce when rarefaction waves within the target material interact to produce tensile stresses exceeding the threshold required for damage initiation. Dynamic damage evolution of materials is closely related to their microstructure, which has been studied by many researchers.[4–8] Grain size and grain boundary, as two of important aspects of material microstructure, play crucial roles in dynamic damage evolution. Grain size can affect the dynamic strength of materials by coordinating the deformation and changing the stress concentration. The special properties of the grain boundary of the material not only play an important function in the physical chemistry of the crystal, but also greatly affect the total performance of materials.[9–13] Under dynamic loading, grain boundary-related deformation and the dynamic segregation of impurity atoms in the grain boundary constitute the origin of the damage, and fracture damage often occurs in specific types of grain boundaries.

The processing of materials results in anisotropy of the microstructure, including grain shape, grain orientation, and lattice shape; these are different in all directions of the original material. Samples cut along different directions show different dynamic macroscopic properties. For example, Clayton[14] has provided the initial microstructural characterization of samples cut along two directions of a tungsten bar and has studied the dynamic thermomechanical response of these samples. The simulations illustrate that the grain shapes and initial lattice orientations within the bulk significantly affect the shape of the incident and reflected stress waves, in addition to the local intensity of materials. With the development of experimental technology, many researchers began to pay attention to the relation between material microstructure and macroscopic response based on the experimental method; however, many reports have focused on the effects of microstructure on pullback measurements in experiments wherein the sam-

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ple showed complete failure and have estimated the effect of microstructure on material strength in terms of the "pullback velocity."[7,8,10] However, the effect of microstructure on the damage distribution has been given little attention. Damage distribution in a material is crucial for the establishment of the damage-evolution model.[15–18] In this study, the evolution process of microvoids near the grain boundary has been studied by impacting different samples cut from the rolled aluminum bar but with different orientations; in addition, the relation between the material strength and microstructure under different pressures has been analyzed, and the effect of microstructure on damage distribution has also been discussed in detail by using both qualitative and semi-quantitative methods.

2. Plate impact experiments

Plate-impact experiments have been conducted using a 100-mm light gas gun. Figure 1 shows a schematic representation of the experimental configuration used. The advantage of this equipment is that it can be used for obtaining the free-surface-velocity profile and the "soft-recovered" sample. The flyer and the target used in the experiments are ultrapure aluminum (purity approximately 99.999%). The diameters of both the flyer and the target are 30 mm and the thicknesses are 3 mm and 6 mm, respectively.

To single out the effect of grain size and arrangement on the dynamic damage evolution, all the samples are cut from the rolling-formed aluminum bar but along two different directions. The sample cut along the direction perpendicular to the aluminum rod is called a "cross-cut" sample, and the sample cut along the direction parallel to its axis is called a "longitudinal-cut" sample. All samples are divided into three groups and are subjected to three levels of shock pressures; the corresponding experimental conditions are listed in Table 1.

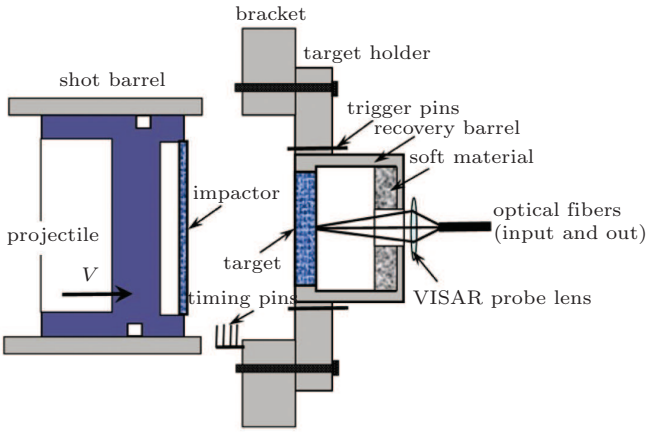


Fig. 1. (color online) Schematic plot of the experimental configuration.

Table 1. Experimental parameters and results of ultrapure aluminum.

Shot No.	Flyer/Sample thickness/mm	Cutting direction	Impact velocity W (m/s)	Pullback velocity Δu_f (m/s)	Shock pressure σ_s/GPa	Spall strength σ_f/GPa	Maximum damage	Damage state
1	3/6	cross-cut	170.0	149	1.26	1.08	0.14	damage with voids
2	3/6	longitudinal-cut	168.9	116	1.25	0.84	0.12	damage with voids
3	3/6	cross-cut	196.9	157	1.47	1.14	0.21	damage with voids
4	3/6	longitudinal-cut	201.0	115	1.49	0.84	0.26	damage with voids
5	3/6	cross-cut	216.0	170	1.61	1.24	0.24	damage with voids
6	3/6	longitudinal-cut	212.0	170	1.58	1.24	0.22	damage with voids

Using the velocity interferometer system for any reflector (VISAR)[19] and "soft-recovery," the free-surface-velocity profiles are obtained and shocked samples are recovered. The effect of microstructure on damage evolution is analyzed. The cross section of the "soft-recovered" sample is ground and polished with a semiautomatic polisher. Subsequently, the polished cross section is corroded for 3–5 minutes with 10% hydrofluoric acid until the grain boundaries are observed with clarity. The cross section is examined with an inverted type-4XC metallurgical microscope for obtaining metallographic photographs. Based on the metallographic photographs, the characteristics of damage nucleation, growth, and coalescence, the damage-distribution feature of materials with different microstructures and the microstructural features causing the differences in macroscopic properties are obtained.

3. Results and discussions

3.1. Characteristics of microdamage nucleation and growth

Because the arrangement of atoms at the grain boundaries of ultrapure aluminum is irregular, dislocations, voids, and impurity atoms gather easily. Under shock loading, the dislocation increases due to the migration of grain boundaries, and microvoids preferentially appear in these positions after samples undergo the tensile stress (Fig. 2(a)). However, not all the grain boundaries produce voids, and a void nucleates most easily in grain boundaries with larger curvature, especially at the position of the intersection of three boundaries. The void grows along the grain boundary under tensile stress after nucleating and becomes a bigger void when it meets adjacent voids (Fig. 2(b)). Moreover, it seems that some voids nucleate within grain interiors. Their nucleation could be related to

grain boundary plasticity, or completely independent.[20,21]

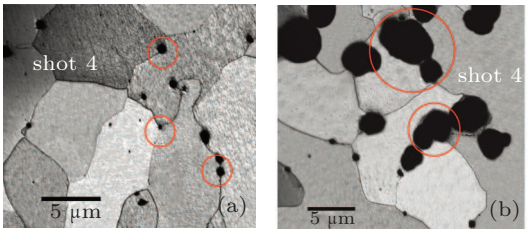


Fig. 2. (color online) Nucleation and growth characteristics of microvoids: (a) microvoids appear at grain boundaries; (b) voids grow along grain boundaries.

In 1996, Canova *et al.*[22] presented two types of damage-growth models to simulate the nucleation features of damage located at grain boundaries. They think that decohesion or fragmentation of the particles is the source mechanism of damage. Escobedo *et al.*[10] also studied the effect of grain size and boundary structure on the dynamic tensile response of copper by plate-impact experiments. They found that the isolated growth and coalescence of microvoids are dependent on grain size and that voids in some particular grain boundaries do not easily nucleate. These research results are in line with the experimental conclusions in our work.

3.2. Macroscopic differences between samples with different grain size and arrangement

An approximate formula can be used for calculating the shock pressure, as follows:

$$\sigma_s = \rho_0 D u = \rho_0 (C_0 + \lambda u) u, \tag{1}$$

where σ_s is the shock pressure, in unit GPa, D is the shock wave velocity, in km/s, $u = W/2$, where W is the impact velocity, in m/s, ρ_0 is the initial density of the materials, in kg/m^3 (2.7 kg/m^3 for Al), and C_0 and λ are the parameters of the Gruneisen equation, which are 5.386 km/s and 1.34[23] for pure aluminum, respectively. The calculated results for the shock pressure are given in Table 1.

Figure 3 shows the free-surface-velocity profiles for the three groups of samples which illustrate the effect of microstructure on the spall signal under different shock pressures. In Figs. 3(a) and 3(b), the pullback velocity (the velocity difference between the first peak plateau and the first valley) of "longitudinal-cut" samples is always less than that of the "cross cutting" samples under lower shock pressure. However, when the shock pressure is higher, there is practically no difference between them (Fig. 3(c)).

The spall strength can be calculated using the acoustic method,[24] which is simplified by ignoring the difference in the unloading wave velocity; the calculated results are listed in Table 1,

$$\sigma_f = \frac{1}{2} \rho_0 c_0 \Delta u_f, \tag{2}$$

where σ_f is the spall strength, in unit GPa, c_0 is the speed of sound in fluid mechanics, which is 5.386 km/s for Al, and Δu_f is the pullback velocity on the free-surface-velocity profile, in unit m/s. Luo *et al.*[25] proposed that the acoustic method only accommodates small perturbations in the density and wave speed at compression, release, and tension states. They also found that the acoustic method is of sufficient accuracy for the Taylor waves, but underestimates square waves. We only want to compare the difference between two kinds of samples qualitatively, so the assumptions made in this work will not influence the result.

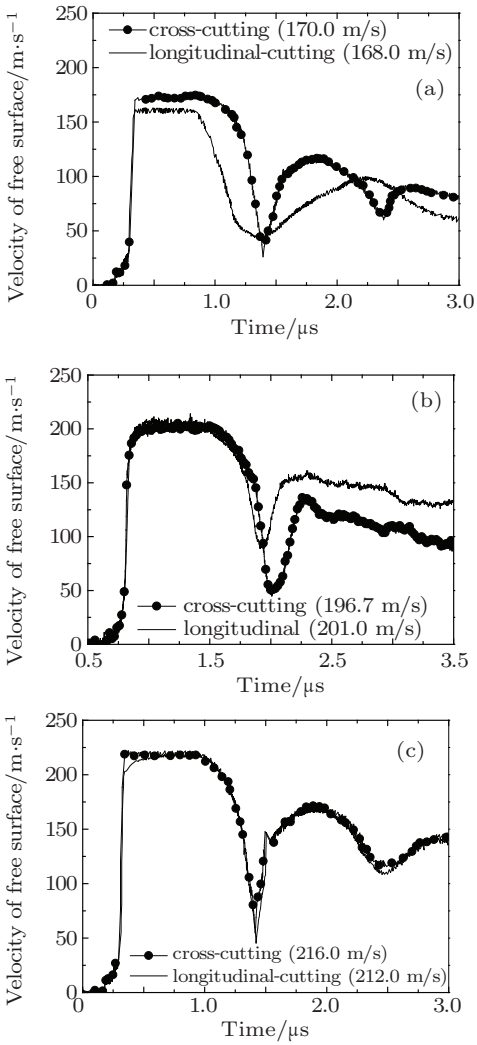


Fig. 3. Comparison of free-surface velocity profiles of "cross-cut" and "longitudinal-cut" samples: (a) shots 1 and 2; (b) shots 3 and 4; (c) shots 5 and 6.

When the shock pressure is 1.25 GPa–1.49 GPa, the spall strength of the "longitudinal-cut" samples is significantly lower than that of the "cross-cut" samples. However, when the shock pressure reaches 1.58 GPa–1.61 GPa, the spall strength of both samples is almost the same. Because the microvoids grow quickly and connect with each other at the candidate spall plane under high shock pressure, the energy is released rapidly and the speed of growth of small voids at the grain

boundary next to the candidate spall plane is restrained, which is the reason for the damage being mainly concentrated on the candidate spall plane. In this case, the contribution of microstructural differences to damage evolution is not obvious. However under lower shock pressure, the damage to materials nucleates or grows gradually, and the process strongly depends on the microstructure; therefore, the effect of the microstructure on the spall strength is relatively weak.

3.3. The causes for the macroscopic differences

Why are there such large differences in the free-surface-velocity profiles for the two samples with different cutting directions under low shock pressure? The qualitative and semi-quantitative analyses are given in the following part.

3.3.1. Qualitative analysis

The damage metallographs of "longitudinal-cut" and "cross-cut" samples, show that the region of damage in "cross-cut" samples is wider and the damage is distributed in an approximately 2-mm range near the candidate spall plane; however, the region of damage in "longitudinal-cut" sample is narrower and the damage is distributed in an approximately 1-mm range near the candidate spall plane. The grain boundaries are oriented along the axial direction of a rolled aluminum bar. Figure 4 shows a simplified scheme of the grain boundaries. The arrangements of grain boundaries are assumed for a multilayer structure (they are simplified to five layers in Fig. 4), and the effective working region of the tensile stress is an approximately 2-mm range in the center of the sample. For the "cross-cut" sample, there are five layers of grain boundaries in the effective working region of tensile stress. Because voids easily nucleate at the grain boundary, the region of damage is wide, and voids coalesce in the grain boundaries along shock direction. However, in the "longitudinal-cut" sample, only the third layer's grain boundary is in the effective working region of tensile stress; consequently, the region of damage is narrow and the damage coalesces in the direction perpendicular to the shock loading.

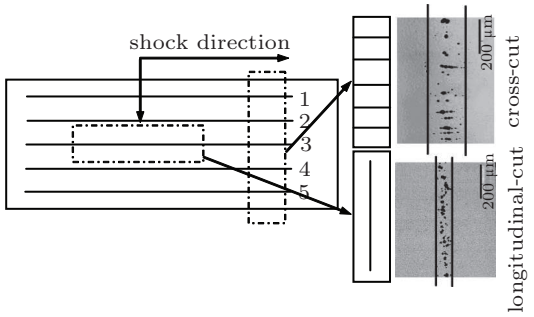


Fig. 4. Simplified scheme of grain boundaries.

3.3.2. Semi-quantitative analysis

Some interesting differences between the two samples can be found by comparing their grain distributions (Figs. 5(a) and 5(b)). After being corroded, the voids are clearer in two samples. Many small voids on the grain boundary are displayed, so the range of damage looks wider than that in Fig. 4. Smaller and non-uniform grains are found in the "cross-cut" sample and the average grain diameter is approximately 0.5 mm. In contrast, larger and uniform grains are found in the "longitudinal-cut" sample, with the average grain diameter being nearly 1 mm. In general, the effect of grain distribution on damage evolution includes the effect of grain size and arrangement. Usually, the smaller the grain size, the better the deformation coordination; when the deformation is uniform, the stress concentration is reduced effectively. Though the number of potential nucleation sites is large, the energy is dispersed and the number of nucleating voids is smaller near the candidate spall plane. This is the reason for the "cross-cut" sample being stronger than the "longitudinal-cut" sample.

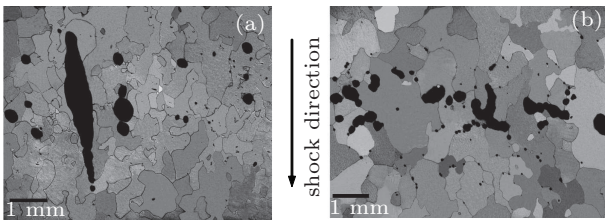


Fig. 5. Grains distributions: (a) "cross-cut" sample (shot 3); (b) "longitudinal-cut" sample (shot 4).

Based on the study of energy release, a semi-quantitative method is used for explaining the differences in strength between the "cross-cut" and "longitudinal-cut" samples. Under an impact load, plastic deformation processes occur. When debonding occurs at the surface of a particle, the work done must be at least equal to the energy required to form the new internal surfaces, just as in the case of ductile void nucleation by vacancy diffusion. Accordingly, the more potential nucleation sites, the greater the number of energy-release sites; thus local expansion of the damage is restrained. The 2-mm area near the candidate spall plane of the two samples is considered for comparing the potential nucleation sites. The number of potential nucleation sites, including voids, and the number of grain boundaries are counted in seven corresponding regions (Fig. 6), and the statistical results are listed in Table 2. Except for regions 4 and 6, there are large differences between the numbers of potential nucleation sites in the other regions. The number of potential nucleation sites in the "cross-cut" sample is larger than that in the "longitudinal-cut" sample. Hence, voids have a connecting tendency in the shock direction in the "cross-cut" sample, but in the direction perpendicular to the shock direction in the "longitudinal-cut" sample. In addition, the main damage area in the "cross-cut" sample is wider than that in the "longitudinal-cut" sample; therefore, the energy required to form the new internal surfaces is scattered and the sample is not fractured easily (Fig. 5).

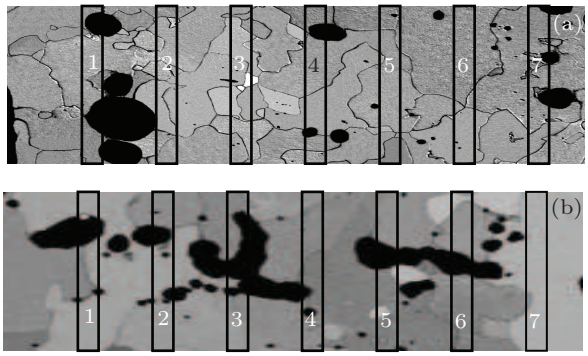


Fig. 6. Potential nucleation sites: (a) "cross-cut" sample (shot 3); (b) "longitudinal-cut" sample (shot 4).

Table 2. The counting results of potential nucleation sites.

Regions for counting potential nucleation sites	1	2	3	4	5	6	7
"Cross-cut" sample	7	10	16	4	7	3	12
"Longitudinal-cut" sample	3	5	3	4	4	3	1

4. Conclusions

The effects of grain size and grain arrangement on the strength and damage evolution of ultrapure aluminum have been studied by plate-impact experiments. The main conclusions are as follows.

(i) Under tensile stress, the microvoid almost nucleates at the grain boundaries and grain boundary triple junctions for all samples, especially at the grain boundaries with larger curvatures. The nucleated voids grow along the grain boundary.

(ii) Under lower shock pressure, the spall strength of the "longitudinal-cut" sample is less than that of the "cross-cut" sample. However, under higher shock pressure, their spall strengths are almost the same due to the rapid release of energy.

(iii) Under lower shock pressure, the region of damage in the "cross-cut" sample is wider than that in the "longitudinal-cut" sample and the number of potential nucleation sites in the "cross-cut" sample is greater than that in the "longitudinal-cut" sample. Therefore, voids have a connecting tendency in the shock direction in the "cross-cut" sample, and in the direction perpendicular to the shock direction in the "longitudinal-cut" sample.

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