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Spall failure of aluminum materials with different microstructures

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ABSTRACT

The effects of microstructure on the spall failure were studied for four aluminum materials by a series of plate-impact spall experiments, including the real-time measurements of the free surface velocity profiles and the microscopic postimpact examination of the soft-recovered samples. Spall strength values are calculated by using the free surface velocity measurements. The high density high purity aluminum (Al HP) exhibits a higher spall strength than the low-porosity pure aluminum. The metallographic examination revealed that it could be attributed to the less impurity in the grain boundaries in the Al HP samples, having a better resistance for void nucleation. The 2024-T4 aluminum alloy exhibits a stronger spall failure resistance than the 7075-T6 aluminum alloy, which is associated with the stronger plastic strain hardening behavior. Comparison among the Al HP, 2024-T4 and 7075-T6 alloys indicates that the differences observed in the rise rate of pull-back are linked with the different active mechanism and growth rate of damage evolution.

1. Introduction

Aluminum and aluminum alloys are recognized as the structural materials most widely used in aeronautics and aerospace industry in the recent several decades because of their high ratio of stiffness/weight and strength/weight. Knowledge of their dynamic deformation and fracture at high-strain rates are inevitably required in a protection consideration of aerospace components against high-velocity impacts, e.g. by particles or meteors during the process of launch, space exposure and re-entry. Among those the so-called spallation is one of the main modes governing shock-induced fracture and fragmentation, which is a kind of internal rupture within a body due to a certain dynamic tensile stress generated by the interaction of rarefaction waves, such as the rarefaction wave of a compression wave reflected from a free-surface (see, e.g. Antoun et al., 2003; Kanel et al., 2004).

The spall behavior of aluminum materials had been extensively studied. A number of researchers focused their attentions on how the spall strength depends on the loading condition, by using plate impact or laser irradiation experiments, It is easy to expect that the peak shock stress may play a key role in spalling. However, not as simple as some one expected, Stevens and Tuler (1971) and Kanel et al. (1996), respectively, observed that the peak shock stress induced by plate impact does not have significant effects on the spall strength of 6061-T6 aluminum and AD1 aluminum. Recently Williams et al. (2012) investigated the effects of both peak shock stress and pulse duration on the spall response of fully annealed 1100 aluminum, and their results showed that the spall strength increases with increasing peak shock stress up to approximately 8.3 GPa, and then a decrease appears at higher shock stresses. This behavior is attributed to two competing mechanisms i.e. the shock hardening and the work softening. By using laser irradiation experiments, Tollier and Fabbro (1998), Dekel et al. (1998) and Wang et al. (2006) found that the spall strength of pure aluminum rapidly increases

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with the tensile strain rate at about $10^6\ s^{-1}$, which was attributed to a change in the spall mechanism. All of those show that the spallation is much complicated than as expected, and further investigations are required.

In addition to the effect of loading condition, more attentions had been devoted to the influence of microstructure on spall failure of aluminum materials. Recently, Chen et al. (2006) reported that the spall strength of single-crystal aluminum is higher than that of polycrystalline aluminum and aluminum alloy. By using the laser-shock-induced spall experiments, the effect of microstructure on spall fracture morphology of thin aluminum targets was investigated by Brewer et al. (2007). They found that, depending on microstructures, the spall fracture surface morphology, could be characterized by brittle intergranular fracture or ductile transgranular fracture, and the spall strength increases with increasing ductile fracture character. By using laser irradiation loading too, Dalton et al. (2011) and Pedrazas et al. (2012) extended the fundamental understanding by examining the effect of impurity particles, grain size and inclusions on the spallation of aluminum. However, an in-depth investigation of the spall response of aluminum materials with varying microstructures is warranted in order to further explore the potential correlations between microscopic structures of material and the continuum spallation measurements.

In this paper, the material investigated is described first, followed by a description of the experimental methods used. The spallation results are then presented and discussed by both the measurement of the free surface velocity profiles and the metallographic examinations of recovered samples. Finally, conclusions are drawn based on the results obtained.

2. Experimental procedures

2.1. Materials

Four aluminum materials were studied in this investigation: high-purity aluminum (Al HP), low-porosity pure aluminum (Low-porosity Al), 2024-T4 aluminum alloy and 7075-T6 aluminum alloy. The Al HP is commercially provided by Guizhou Aluminum Factory of China in the form of rods with a purity greater than 99.999% and its main impurities include Si (1.0–2.0 ppm), Fe (1.0–2.4 ppm),Cu (1.0–2.1 ppm), Pb (0.1 ppm), Zn (0.5 ppm), Ga (0.1–0.18 ppm), Ti (0.1–0.8 ppm), Cd (0.1 ppm), and In (0.1–0.13 ppm). The low-porosity Al is made of 99% purity aluminum powder with average particle size of 6 μm by the solid-phase sintering under the temperature of about 580 °C in a duration of three hours. The average bulk density of the as-received sample is 2.61 g/cm^3, and the initial porosity is about 3.3%. The aluminum alloys 2024-T4 and 7075-T6 were received as as-extruded bar commercially produced by ALCOA. Their chemical compositions are given in Table 1. The 2024-T4 is the most widely used alloy of the 2000 series, experiencing a natural aging after cold working. The formation of a high-volume fraction of Guinier–Preston zones and coherent $CuMgAl_2$ precipitate phase in the grain interiors, as well as by the presence of Al–Cu–Mn dispersions, provides a moderate yield strength but good damage tolerance. The 7075-T6 is the most widely used alloy of the 7000 series alloy, having the highest strengths by far. Its high strength is resulted from the precipitation of coherent $MgZn_2$ phase in the grain interiors and non-coherent $MgZn_2$ along the grain boundaries. For all four Al materials, their as-received microstructures before tests are shown in Fig. 1(a)–(d).

Table 1
Main chemical composition of the investigated aluminum alloys (mass%).

Alloys	Cu	Mg	Zn	Fe	Mn	Cr	Si
2024-T4	3.8	1.2	0.2	0.38	0.28	0.1	0.38
7075-T6	2.0	2.33	5.52	0.38	0.28	0.25	0.20

2.2. Plate-impact experiments

The planar symmetrical impact spall experiments were preformed by using a 57 mm light gas gun. Fig. 2 is a schematic of the experimental setup. In a symmetric impact configuration, two sets of the compression wave are generated at the flyer-target interface upon impact, traveling in opposite directions within the flyer and target, respectively. At the free surfaces, the compression shock waves are reflected as rarefaction waves. When the rarefaction fans from the flyer and the target free surfaces interact, a region of tensile stress is generated. In this paper we assume that if the tensile stresses such generated are greater than the threshold stress required for damage initiation, growth, and coalescence, and then the material fails by spallation.

To monitor the process of spall fracture, time-resolved free surface velocity profiles of the shocked sample were measured with a Velocity Interferometer System for Any Reflector (VISAR) technique, similar to that developed by Barker and Hollenbach (1972), and further modified by Hemsing (1979). Early workers, assuming an instantaneous occurrence of spallation, simply related the "pull-back" in free surface velocity to the instantaneous spallation. However, spallation is in fact a cooperative nucleation, growth, and coalescence process of spall damage, and thus the "pull-back" signal may not correspond to a complete spallation but an incipient spalling, as pointed by e.g. Zurek et al. (1996). Since the spalling occurs inside the sample, the free surface velocity profile only indirectly presents a consequence of the interaction between the wave propagation and the damage evolution layer, so it is important to combine the free surface velocity measurements with another diagnostic methods, such as the microstructure examination of the shocked specimen. Consequently a soft recovery technique for the shocked specimen was adopted. As shown in Fig. 2, on the one hand a target holder is specially designed, of which the diameter is smaller than that of projectile so that the projectile can be stopped to prevent a further impact on the shock-damaged specimen. On the other hand a recovery barrel filled with soft damping material is attached to and behind the target holder to slow down and protect the flying shocked-specimen. The satisfactory recover of shocked-specimens indicate the success of such a technique. The