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Spall behaviors of high purity copper under sweeping detonation

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ABSTRACT

Suites of sweeping detonation experiments were conducted to assess the spall behavior of high purity copper samples with different heat treatment histories. Incipient spall samples were obtained at different sweeping detonation condition. Metallographic and Electron Backscattered Diffraction (EBSD) analyses were performed on the soft-recovered samples. The effects of grain boundaries, grain size, crystal orientation and loading direction on the spall behaviors were discussed. Spall plane branching was found in the main spall plane of the damage samples. For similar microstructure, the area of voids increase with the increase of shock stress, and the coalescence of voids also become more obvious. Results from EBSD analysis show that the grain sizes were decreased and the grains were elongated along the direction of the plate width. Triple junctions composed of two or more general high angle boundaries are the preferred locations for intergranular damage. Voids prefer to nucleate in the grain boundaries composed of grain with high Taylor Factor (TF) than other grains. The damage areas in the grains with high TF are more severe. Boundaries close to perpendicular to the loading direction are more susceptible to void nucleation than the boundaries close to parallel to the loading direction, but the difference of voids nucleated in these two boundaries is less significant than the results obtained by plate impact experiment. It would be caused by the obliquity between the shock loading direction and the plate normal.

1. Introduction

Spall failure is the predominant mode of failure in metallic materials subjected to shock loading. Spall failure in ductile metals is a process of void nucleation, growth and coalescence [1–3]. Extensive work has established that spall is a complex process strongly influenced by many factor, such as grain boundaries, inclusion, loading stress, pulse shape [4–7] etc. The pulse shape has an important impact on spall behavior. Gray et al. [8] showed that high-explosive-driven sweeping-wave loading of Ta has been observed to yield lower spall strength than previously documented for 1-D supported-shock-wave loading and to exhibit increased shock hardening as a function of increasing obliquity. Jarmakani [9] has demonstrated that the spall strength of vanadium obtained from laser compression is higher than the experimental results obtained using gas guns.

Plate impact experiments offer several advantages to the investigation of dynamic tensile damage over other techniques. Most of the researches on dynamic fracture have been carried out under plate impact (ideal one-dimensional loading). These researches have provided a wealth of experiment data and insight concerning the influence of microstructure on the spallation response of materials. However, in practical application, spall is a common of damage occurred in non-ideal one-dimensional condition. Fewer researchers have studied the spall behaviors under such condition. Gray et al. [10] investigated the shock-loading of copper in contact with a high explosive (HE) experiences a triangular wave loading profile in contrast to the square-wave loading profile imparted via the impact of a flyer plate. Hull et al. [11] investigated damage generated in AISI 4130 steel by the combined effects of oblique drive and interacting detonation waves.

Therefore, the main objective addressed in this study is to examine the spall behaviors under non-ideal one-dimensional condition and elucidate the effects of microstructural details on spall behaviors. For this purpose, sweeping detonation are performed on high-purity copper samples at low peak compressive stresses, such that the tensile stresses developed within the target material

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during the experiment is not sufficient to cause complete separation. The damage fields are characterized by means of optical and electron backscatter diffraction (EBSD) microscopy. The combination of these experimental techniques leads to a more comprehensive understanding of the damage evolution.

2. Experimental procedures

2.1. Materials

All samples were prepared from 99.99% pure oxygen-free high-conductivity (OFHC) copper rolled plates. Annealed samples underwent annealing process in air at 973 K (700 °C) for 1 hour to produce uniform microstructures. Thermo-mechanical treatments (TMT) samples underwent the same annealing process and extra two sequential TMT process. The first TMT processing step was 75% cold rolling deformation followed by 3 min annealing in air at 500 °C. The second TMT processing step was 10% cold rolling deformation followed by 5 min annealing in air at 650 °C. To eliminate the effect of oxide skin, the surface of all samples were removed with thickness of 0.5 mm, All samples were process to $100 \times 60 \times 6$ mm^3. The average grain sizes of the annealed samples and TMT samples were 21.67 and 2.45 μm. The grain sizes were measured using EBSD data including twin boundaries. The results of the metallographic characterization for the samples are shown in Fig. 1.

2.2. Sweeping detonation experiments

Dynamic testing was conducted at China Academy of Engineering Physics (CAEP). Fig. 2 is an illustration of the experimental set-up for sweeping detonation. The powder explosive was filled in the cover plate through the explosive-filled hole. The charge size is 80 mm long, 40 mm wide, 3 mm or 4 mm thick. The exploding bridge wire was positioned in the center of explosives. The explosives were detonated at 20 kV, and were initiated simultaneously along a line at all its points. This line was normal to the direction of detonation motion. To monitor the process of spall fracture, time-resolved free surface velocity profiles of the shocked sample were measured with Doppler Pins Systems (DPS). The measurement points were located in the center of the samples. Two points were measured in every sample. The free surface velocity histories profiles can be found elsewhere [12]. The Experimental parameters for the sweeping detonation experiments are listed in Table 1.

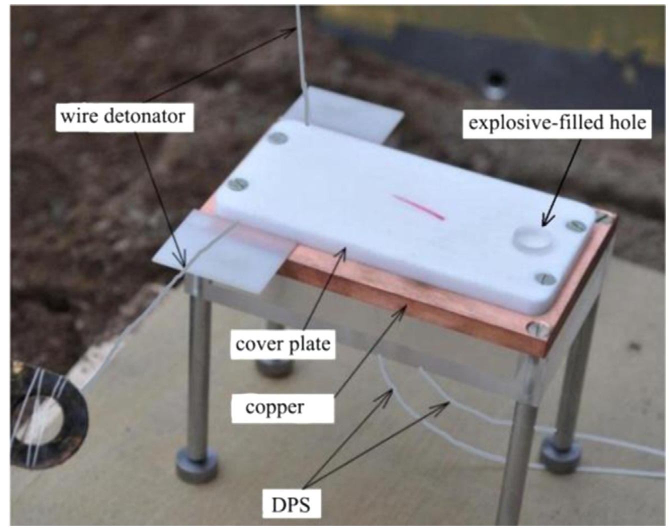

Fig. 2. Experimental set-up for sweeping detonation.

Table 1
Experimental parameters for the sweeping detonation experiments.

Sample number	Explosive type	Heat treatment condition	Thickness of explosive(mm)	Charge density (g/cm3)
PA3	PETN	Annealed	3	0.882
RA3	RDX	Annealed	3	0.915
RA4	RDX	Annealed	4	0.920
RT3	RDX	TMT	3	0.918
RT4	RDX	TMT	4	0.925

2.3. Metallography and EBSD analyses

Following the detonation experiments all samples were soft-recovered. To characterize the spall damage and microstructure, the samples were examined using optical microscopy. All samples were cut into two halves along the dotted line in Fig. 3 with electrical-discharge machining. The samples were prepared according to the standard metallography.

To further assess the differences in the damage evolution for the samples with different heat treatment histories, EBSD analyses were performed on the samples before and after detonation. A schematic of the location of the post-detonation samples with respect to the surface is shown in Fig. 3. After mechanically

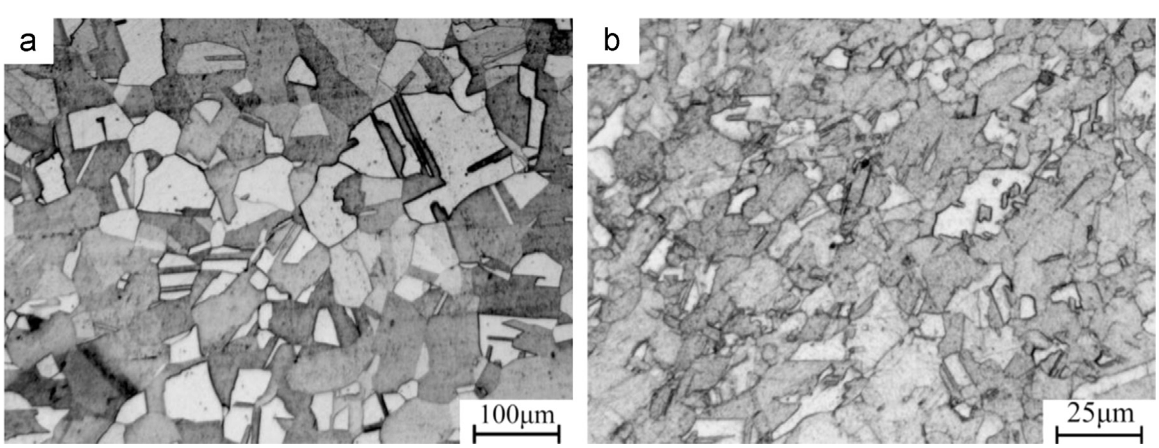

Fig. 1. Optical micrographs of the samples before detonation; (a): annealed. (b): TMT.