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Effects of the phase interface on spallation damage nucleation and evolution in multiphase alloy

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ABSTRACT

The spall behaviors of Cu-34%Zn-3%Pb leaded brass samples with annealing and cryogenic treating conditions were dynamic loaded using one-stage light gas gun experiments under ~1.515 GPa shock pressure. The effects of α/β phase interface and Pb/matrix phase interface on dynamic damage nucleation, growth, and coalescence in leaded brass specimens were investigated by multidimensional testing techniques. Experiment results showed that voids of incipient spall were mainly nucleated in the interior of the Pb-phases with signs of melting, and a small number of voids were nucleated in α-phase, and both are not nucleated at the interface which contradicts the damage fracture theory under quasi-static loading. Due to the effect of reflection and transmission of shock wave at the phase interface, when the shock wave propagates from α-phase with higher impedance to Pb-phase or β-phase with lower impedance, a tensile pulse will be formed within α-phase. If the tensile pulse has sufficient amplitude voids would be nucleated in α-phase. On the other hand, it is considered that the asymmetry high compression zones in the center of the lead-phase with low impedance were formed by the shock wave convergence effects of matrix/lead quasi-spherical interface, which caused adiabatic temperature rise exceeded melting point of lead due to severe plastic deformation, and finally led to local melting and void nucleation in the center of the lead-phase rather than the tensile stress.

1. Introduction

Spallation is closely related to the dynamic unloading behavior of the material. Tensile stress was produced by the collision of two rarefaction waves with the opposite direction of propagation under shock loading, which caused micro-damage nucleation, growth, coalescence and ultimate fracture within the materials [1–3]. The spallation researches of metal materials have very important application background in the field of high speed collision, explosion, aerospace aircraft, armor protection, and so on. So the studies of spallation have important scientific significance and engineering application values. However, due to the need of weapon physics research, the present spallation studies have mainly aroused extensive attention from the physical and mechanical researchers, lacking the related interpretation of the material science.

The phenomenon of spallation was firstly discovered in the early 20th century by Hopkinson [4], that a spall scab was found at the back of low carbon steel sample after the explosion on the surface by nitrocotton explosive. But spall had been widely given attention until post-war II due to the rapid development of military industry and the urgent needs of high-end military engineering design. In 1983, the previous main research results of spallation had been systematically summarized by Meyers et al. [5]. Davison et al. [6] and Curran et al. [1] had a comprehensive review on the loading technologies, measurement diagnosis technologies and experimental results of spall. Antoun et al. [3] made authoritative comments on the history and present situation of spallation. The latest research results and developments were introduced by Williams et al. [7] in 2010.

"Interface" is a very important microstructure part of materials, and it's the key factor that affects the performance of materials because it has many functions, such as transmission, block, absorption, scattering, induction, and so on. Multiphase alloys have

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both the phase interfaces and grain boundaries. Phase interface is the interface of two crystals which have different crystal structures or different lattice parameters with the same crystal structure. Grain boundary is the interface between two grains with same crystal structure but different crystal orientations in a polycrystalline material. Phase interfaces and grain boundaries will inevitably affect the transmission of shock wave in materials under dynamic loading, and then have significant effects on void nucleation, growth of spallation and ultimate fracture which grows along the "interface" by voids. A lot of previous spall works had focused on the study of single-phase pure metal, and scholars generally believe that micro voids prefer to nucleate at the "grain boundary" [8–11]. The present author [12–14] also studied the influence of "grain boundary effect" on the spallation behavior of high purity copper, that is the effect law and mechanism of grain boundary types, grain orientation and grain size on the spall behavior of high purity metal. However, multiphase alloys are the widely used materials in engineering. Nowadays, the spall studies about the influence of "phase interface" are rare. The influences mechanism and laws of phase interface on the nucleation and evolution of dynamic damage are not fully understood.

It is well known that due to the differences of physical and mechanical properties between two phases, the stress/strain mismatch is caused easily at the phase interface. So the phase interface seems to be a "weak link", and phase interface is the preferred position of voids nucleation and growth, which is the general rule based on the theory of damage fracture under quasi-static loading [15]. However, according to the impact theory [2], phase interface can produce interaction and reflection of shock wave on the process of high strain rate dynamic loading (namely the process of transmission of stress wave in metals). So under dynamic loading conditions, what is the influence of phase interface on voids nucleation and growth of spallation? And what is the effect laws and mechanism? That is a key issue to be solved in many fields such as aerospace, aviation, military industry and so on, but it still lacks relevant research and cognition.

At present, the main studies about spallation of multiphase alloys are as follows: Hixson et al. [16] conducted the experiments on aluminum containing alumina impurities and Cu/Nb composite, found that the spall behavior of samples had a dependence on the interface. Researches by Thissell et al. [17] found that the voids nucleation of incipient spall played a leading role on the distribution of final voids; the spall strength values of two copper samples of different purity could have a difference of 50% due to the difference characteristics of the second phase particle. Minich et al. [18] studied the spall behavior of single crystal copper with SiO_2 impurities, found that the stress of void nucleation was decreased by the small, hard SiO_2 particles. Similarly, work by Fensin et al. [19] that studied the spall behavior of purity copper and Cu-1wt%Pb dual-phase alloys under shock loading, reveals that the damage nucleation degree of purity copper without lead significantly reduced but the rate of damage evolution was much faster. Han et al. [20] studied the dynamic deformation and failure of Cu-Nb layered nanocomposites (with a nominal layer thickness of 135 nm) under plate impact, and found that incipient voids tend to nucleate within the Cu phase rather than nucleate on the Cu–Nb interfaces. Furthermore, experiments by Fensin et al. [21] on three kinds of polycrystalline materials: Cu, Cu-24 %Ag, and Cu-15%Nb alloys, preliminarily showed that: in CuAg and CuNb alloys, voids nucleated within Ag phase and on the Cu side of the Cu/Nb interface. These works demonstrate that bimetallic interface has important effects on voids nucleation of spallation.

Although the previous experimental observations show that the presence of phase interface has effects on the spall strength of materials, but the effects of phase interface on the position of damage nucleation and concrete mechanism of damage evolution in alloys are still unclear. At present, researches about the influence of "phase interface" on the spall behaviors are not studied thoroughly.

In this work, the HPb63-3 lead brass (with α-phase, β-phase and nearly spherical Pb-phase) was chosen as the research object. The influence laws and mechanism of "phase interface" on the spall behaviors of leaded brass were investigated, and the mystery of "phase interface effect" on the spallation of alloy was tried to be revealed.

2. Experimental design and procedures

2.1. Materials

To thoroughly understand the influence mechanism of different impedance phases on multiphase alloys under dynamic loading, we have chosen the Cu-34%Zn-3%Pb leaded brass as the experimental material. Cu-34%Zn-3%Pb leaded brass is a class of copper alloy with dual-phase(α+β) matrix, with a composition of ~63 wt% Cu, ~34 wt% Zn and ~3 wt% Pb. The lead cannot easily dissolve into the dual-phase(α+β) matrix, but diffusely distribute in α-phase, β-phase and α/β phase boundaries as the form of dissociate Pb-phases. α-phase is a solid solution with good plasticity. Because the α-phase is precipitated along the grain boundaries of β-phase, the α-phase is mainly distributed along the grain boundary of β-phase (an ordered solid solution with CuZn matrix). Therefore the so-called "grain boundary" actually is the phase interface.

In order to change the component proportion and sizes of lead phase and α-phase, two original Cu-34%Zn-3%Pb leaded brass samples were processed by the following steps: sample one was annealed at 923 K (650 °C) for 1 h and air-cooled, and sample two was treated with cryogenic treatment at 77 K (−196 °C) (in liquid nitrogen) for 24 h after the same annealed heat treatment.

The optical micrographs of Cu-34%Zn-3%Pb brass samples before shock loading are shown in Fig. 1.

The area percentage of Pb-phase and α-phase were measured by means of optical microscopy with the help of software Image Pro Plus (IPP), as shown in Table 1. The area percentage of Pb-phase in sample one and two were are both increased, while the area percentage of α-phase were decreased gradually. And the average grain sizes of sample one and two were found to be nearly the same (~70 μm) after the same heat treatment because grain sizes of samples would not change during the cryogenic treatment.

These results can be explained as follows: Pb-phases (melting-point of lead:600.5 K (327.5 °C)) were in molten globule state in the process of 923 K (650 °C) high temperature heat treatment, and the nearby small Pb-phase molten globule in original samples were converged together into big Pb-phase molten globule. Meanwhile, β-phase had grown up gradually, and a small amount of α-phase would transform into β-phase after the rapid air cooling to room temperature. As a result, the area percentage statistics of Pb-phases were increased by ~78% more than the original sample after the heat treatment. As for sample two, the dual-phase(α+β) matrix had a greater degree of supersaturation and instability in the process of cryogenic treatment, part of the supersaturated α-phase would transform into β-phase during the process of rapid warming to room temperature. Moreover, the solubility of Pb in brass is lower at 77 K (−196 °C). Pb-phases were precipitated slowly from the matrix of brass after the long holding time of 24 h, then the irregular sphere Pb-phase became bigger in sizes. So samples two increased by ~82% more than samples one on the area percentage statistics of Pb-phases, and the area percentage of α-phase was decreased with small amplitude. It is worth noting that the number of Pb phase decreases as the percentage of area increases. This is because the small Pb-phase in the sample two agglomerated to larger Pb-phase after the cryogenic treatment.