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Effects of the phase interface on initial spallation damage nucleation and evolution in dual phase titanium alloy

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ABSTRACT

The Ti-6Al-4V dual phase alloy samples were dynamic loaded by one-stage light gas gun experiment and samples with initial spallation were softly recovered. During the loading experiment, the velocity of free surface particles was measured by photonic doppler velocimetry (PDV). The effect of α/β phase interface on nucleation, growth, and coalescence of dynamic damage in Ti-6Al-4V were investigated by 2-D or 3-D testing techniques, such as optical microscopy(OM), x-ray computer tomography(XRCT), and electron backscattered diffraction(EBSD). The results showed that the majority of voids were nucleated within α phases, rather than on the α/β phase interface as predicted by quasi-static damage theory. Due to the effects of reflection and transmission of shock wave at the phase interface, a tensile pulse would be formed within α phase when the shock wave transmit from α phase with high impedance to β phase with low impedance. When this tensile pulse was large enough, voids would be formed within α phase. The analyses of OM and XRCT indicated that the voids at the beginning of nucleation were nearly spherical, then grew up along the direction of 45° with the shock loading direction, and finally the rod-shaped voids were formed. Besides, the voids were not randomly nucleated within α phase, and the EBSD analysis showed that the voids were mainly nucleated at grain boundary triple points which composed of grains with large difference of Taylor Factor(TF) value within α phase. This is because the difference of plastic deformation capacity of this grains is larger, and it is easier to produce stress concentration. Thus these sites became the prior nucleation position of voids.

1. Introduction

Spallation is a typical material dynamic failure mode, which is closely related to the dynamic unloading behavior of materials; the tensile stress was produced by the collision of two rarefaction waves under shock loading, which caused micro-damage nucleation, growth, coalescence and ultimate fracture within the materials [1,2]. Due to the research on the phenomenon of spallation is not only closely related to military engineering, aviation and space engineering, but also involves various disciplines, therefore the spallation research has important practical and theory significance, and has been widely investigated. However, because of the need of weapon physics research, the spallation behavior is mainly concerned by engineering physics and mechanics workers, and the related researches of material science were seriously lacking.

The discovery of spallation began in 1914, Hopkinson [3] put a piece of dynamite on the steel plate, and found that there was scab flying out of the back surface. He analyzed the experimental phenomena and believed that the spallation was caused by the interaction of shock wave generated by the explosion in the material, which caused the material to be subjected to tensile stress to produce the scab flying out. In the early 1950s, Rinehart [4] used the method of Hopkinson to obtain the spallation state of some materials such as aluminum alloy, brass, copper and steel, and they thought the spall strength is one of the material characteristic parameters. Meyers and Aimone [5] had made a systematic summary and review of the main research conclusions about the damage of spallation before 1983. Davison and Grady [6], as well as Curran and seaman [7], had comprehensively reported on various loading techniques, diagnostic methods and experimental results in the field of spallation research. Antoun et al. [1] made authoritative comments on the study history and current situation of spalltion. Williams et al. [8] introduced the latest research findings and advances.

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With the further study on the damage of spallation, the influences of material's shape, microstructure and methods of dynamic loading on the fracture resistance of materials had been the hot spots of research in the field of dynamic tensile fracture. Koskelo [9] discovered that the damage of plate impact appeared in the regions where prone to generate a large number of dislocation during the shock-loading, and the damage continued to grow with the cyclic effect of the subsequent shock wave. According to Furnish et al. [10], the nucleation position of tantalum metal spalled samples in the plate impact test was related to the original grain size of the sample, and compared with the high stress state, the effect of microstructure on the spallation behavior under the low stress state is more obvious. In poly-crystalline copper, the study confirmed that grain boundary is the main nucleation point of voids in the primary spallation samples [11,12]. The author [13–16] also used the high purity copper as the research object, and studied the influence law and mechanism of different loading methods, shape of sample and the "grain boundary effect"(grain boundary type, grain orientation and grain size) on the spallation behavior of high purity metals. A great deal of previous work had focused on the study of spallation of single-phase pure metal, however, multiphase alloys were widely used in modern engineering. There were few researches on the influence of the phase interface, and the influences law and mechanism of the phase interface on the nucleation and evolution of dynamic damage were not fully understood at present.

Both phase interface and grain boundary were present in multiphase alloy. Phase interface refers to the interface consists of two pieces of crystal with different structure or the same structure but different lattice parameters, and grain boundary refers to the interface between the two grains with same structure but different orientation. It is well known that due to the differences of physical and mechanical properties between two phases, the stress/strain mismatch is easily generated in the phase interface. So the phase interface seems to be a "weak link", and it 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 [17]. Under the impact theory [1,2], dynamic loading process is the propagation of shock wave within material, and phase interface will generate the effect of interaction and reflection on shock wave. Simultaneously, the different properties and performance of different phase may also affect the spread of shock waves. So the research on the influence law and mechanism of the phase interface on the spallation behavior was of great significance for us to further study the spallation.

At present, there are few researches on the effect of phase interface on the behavior of spallation. Work by Minich et al. [18] on two phase materials like single crystal copper with SiO_2 inclusions showed that the presence of small, hard SiO_2 precipitates reduced the stress required for voids to nucleate in this material as compared to that for pure Cu. Similarly, Christy et al. [19] examined inclusions present at a grain boundary in Cu revealed that voids preferred to nucleate at these inclusions along the grain boundaries. Fensin et al. [20–22] used the single phase pure copper, Cu-Pb, and Cu-Ag alloy as the objects and found that in the alloy containing the second phase, different content of the second phase will affect and the spall strength and damage degree, and the phase interface will affect the position of the voids. Cerreta et al. [23] studied the spallation behavior of pure copper and Cu-1 wt% Pb alloy under impact loading. The results showed that there was a significant reduction in the damage nucleation of the pure copper without adding lead, but the corresponding velocity of damage evolution was faster. Han et al. [24] 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 the incipient voids tend to nucleate within the Cu phase rather than nucleate along the Cu–Nb interfaces. This finding contradicted the general thinking of failure started from interfaces. Yang et al. [25,26] studied the nucleation and growth characteristics of the initial spallation of lead brass, and found that the distribution position of the microvoids was close to the spalled layer and most of the voids were nucleated in the lead phase. Although the above researches and experiment phenomenons showed that the phase interface will affect the spallation strength, but its influences law and mechanism for the nucleation position and evolution of voids in the initial stage of spall were still not clear. At present, there is a lack of systematic and in-depth study on the influence of the phase interface on the behavior of spallation.

Al-6Ti-4V has good plasticity, super-plasticity, weld-ability and corrosion resistance, etc. And because of its excellent mechanical properties as well as the characteristics of easy processing, it has long been used as the candidate materials of military industry manufacture.

2. Experimental design and procedures

2.1. Materials

In order to investigate the influence of phase interface on the void nucleation of spallation, Ti-6Al-4V dual phase alloy was used as the experimental material. In order to study the effect of phase composition on the spallation behavior simultaneously, different heat treatment regimes were used to obtain two samples with different phase content and grain size. The phase transformation temperature of Ti-6Al-4V is 975 ± 10 °C, which means that when temperature close to 975 °C, the α phase would gradually converted into β phase, so the different solid solution temperature can get different phase composition. The two kinds of heat treatment regimes: (1) solution under 937 °C for 2 h, 700 °C water quenching for 2 h, air cooling; (2)solution under 947 °C for 2 h, 700 °C water quenching for 2 h, air cooling. Fig. 1 shows the metallographic diagram.

As can be seen from Fig. 1, both samples were composed of α phase (white) and β phase(gray). The composition of α phase and the grain size of two samples were calculated by IPP (image pro plus) software as shown in the Table 1:

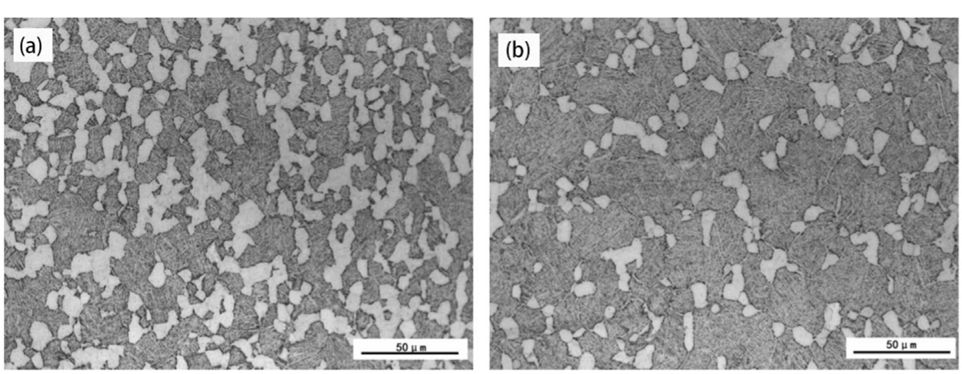

Fig. 1. Metallographic diagrams of two samples after different heat treatment: (a)Sample one (b)Sample two.