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Damage evolution and distribution of interpenetrating phase composites under dynamic loading

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Abstract

The objective of this paper is to investigate the damage evolution of ceramic-metal interpenetrating phase composite (IPC) under dynamic loading. Uniaxial dynamic compression loading was performed to characterize the failure of SiC_{3D}/Al composite with 20% porosity using a modified Split Hopkinson Pressure Bar (SHPB). A micro CT technology is utilized to acquire SiC skeleton scanning images. 3D FE (finite element) model of SiC_{3D}/Al was generated and was applied based on the experimental data. SEM and computer simulation results were employed to study the damage evolution in IPC. The experimental and simulation results demonstrated that there were double cones formed within the IPC cylinder without lateral confinement under uniaxial dynamic compression. The damage initiation and damage extension direction were determined by the shear stress. The synergistic mechanical constraint effect provided by the interpenetrating metal and ceramic phase conduced the fracture cone feature, which was significantly different from the splitting feature of ceramic materials.

Keywords: Interpenetrating phase composites; Damage evolution; Damage distribution; Shear stress; Synergistic mechanical constraint

1. Introduction

Ceramic material has been widely used in armor industry for low density, high compressive strength, and other attributes [1–7]. However, because of the low fracture toughness and high propagation rate of cracks, ceramics were apt to split along the loading axis under high strain rate loading without lateral confinement [8]. Paliwal and Ramesh [9] observed a large number of longitudinal cracks which divided the sample into thin columns without confinement. Chen and Rajendran [10] found that cracks inside the ceramic with lateral confinement would propagate to form conical surface. A planar confinement method has been designed by Ramesh et al. [11], and the results indicated that shear behavior had a significant influence on damage process for ceramics under dynamic loading with confinement. Chen and Ravichandran [12–14] proposed that damage in brittle solids would degrade shear strength and result in localized faulting, which could explain the transition from brittle to ductile behavior of the samples under moderate confinement. Huang and Subhash [15] had investigated dynamic damage evolution character when lateral confinement was conducted on ceramics. They observed the transition of fracture from brittle to ductile when the confinement was increased to a high degree, which provided evidence in supporting the damage accumulation model. Luo and Chen [16,17] found that the ceramic rubble could remain interlocked under moderate lateral confinement and retain the load-bearing capacity under two consecutive stress pulses.

Horii and Nemat-Nasser [18] had studied the failure criterion of brittle solids. The micro cracks nucleated at the tips of micro-cracks which induced the damage [19]. In the earlier time, Sammis and Ashby [20,21] found that when the confinement stress reached a critical value, micro-cracks propagated stably until they interacted with each other, and then led to the final failure step by step. With the linking process of adjacent micro-cracks in the specimen, the stress

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field around the wing-cracks will influence the damage evolution process [22,23].

Ceramic-metal Interpenetrating phase composite (IPC) shows great industry application potential for the special reinforcement structure, many investigations on preparing, characterizing and modeling of IPC have been reported [24–26]. For ceramic matrix IPC, ceramic phase volume content is more than 60%, which provides the material high strength as ceramic, and the remaining ductile metal phase enhances the fracture toughness through interfacial bond [27,28]. And the results have recognized that the interpenetrating phase structure of composite contributes to the excellent performance under dynamic load.

The Finite Element Method (FEM) has been used for describing the dynamic deformation and damage processes of ceramic [29] and composites [30]. The simulation results can indicate the influence of structural feature, interfacial separation and damage accumulation. The traditional 3D model was based on continuous mechanics which was homogeneous materials model. To visualize and to understand material's microstructure, the technique based on the real material was used to build the real 3D composite material finite element model [31].

Current investigation on the fracture character of IPC was always under quasi-static load, the mechanism of dynamic failure character of IPC has not been fully understood, and the effect of stress field on damage evolution remains unclear. In this paper, the fracture characters of IPC composites were investigated with dynamic compression. The formation and the propagation of the damages in IPC and the effect of shear stress field on damage evolution progress were studied.

2. Experimental procedures

2.1. Materials

The interpenetrating phase SiC_{3D} /Al composite was fabricated by porous SiC and pure Al. The porous SiC framework with open porosity of 20% in volume fraction was prepared by vacuum pressure infiltration process.

The basic elastic properties of SiC_{3D}/Al composite were Young's modulus of 340 GPa and Poisson ratio of 0.12. The density of the composite was 3.1×10^3 kgm^{-3} determined by Archimedes' method. The material was machined into cylindrical specimens with 6 mm in diameter and 6 mm in height. The end surface was ground and polished to 1 μm tolerance and the opposite face was polished parallel to 5 μm in tolerance.

2.2. Dynamic uniaxial compression experiment

2.2.1. Split-Hopkinson pressure bar

The uniaxial dynamic compression tests were carried out with Split-Hopkinson Pressure Bar (SHPB). The schematic of the experimental system is shown in Fig. 1. The incident and transmitter bars were 14.5 mm in diameter and 1200 mm in length. The bars were made by maraging steel with Young's modulus 200 GPa and density 8100 kg/m^3. Impedance-matched tungsten carbide platens were jacketed by high strength steel sleeves with shrink-fit technique, and the jacketed platens were inserted between the specimens and the bars, to protect the bar end surfaces. The strain rate was 880 s^{-1} and the deformation amount was controlled by steel rings to obtain damage containing samples with a given set of strain.

2.2.2. Pulse shaper

Shape of the incident pulse was controlled by annealed copper pulse shaper placed on the end of the incident bar, which was impacted by the projectile. The pulse shaper was used to achieve ramp loading and ensure the equilibrium of stresses in the specimen simultaneously.

2.3. Modeling and computation of IPC

In order to make a detailed analysis of specific failure features of SiC_{3D}/Al composite under dynamic loading, the finite element model of this composite based on real microstructure was established by CT technology. The simulation of dynamic deformation process was carried out with LS-DYNA. Johnson–Holmquist and Johnson–Cook constitutive models were employed to describe SiC ceramic and Al metal phase. The material parameters are shown in Tables 1 and 2.

2.3.1. CT images

SiC_{3D} /Al composite was prepared with ceramic skeleton infiltrated with Al phase. In order to get the 3D dimensional space structure feature of composite, ceramic skeleton was scanned by a Sky-Scan1172. This technology was based on X-ray radiography which allowed three dimensional internal structure of a specimen to be determined non-destructively. The voltage and current were 50 kV and 800 μA, respectively. Transmission X-ray images were recorded at 0.4° rotational steps for 180° of rotation. Subsequently, X-ray images were reconstructed into cross-sectional images using the Sky-Scan's

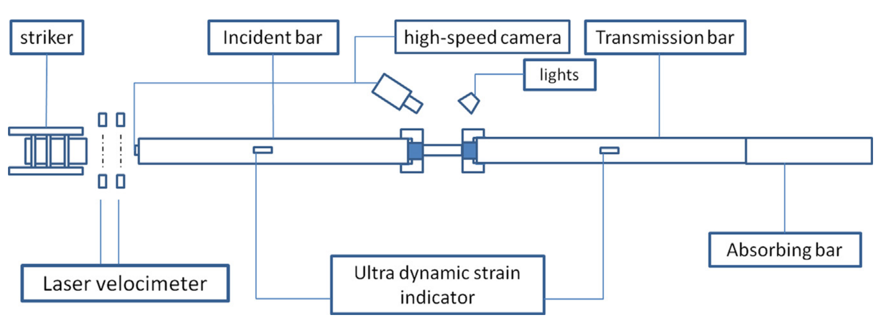

Fig. 1. Schematic illustration of the experimental setup for dynamic fracture.