CP620, *Shock Compression of Condensed Matter – 2001*
edited by M. D. Furnish, N. N. Thadhani, and Y. Horie

INFLUENCE OF INTERFACE SCATTERING ON SHOCK WAVES IN HETEROGENEOUS SOLIDS

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Abstract. In heterogeneous media, the scattering due to interfaces between dissimilar materials play an important role in shock wave dissipation and dispersion. In this work the influence of interface scattering effect on shock waves was studied by impacting flyer plates onto periodically layered polycarbonate/6061 aluminum, polycarbonate/304 stainless steel and polycarbonate/glass composites. The experimental results (using VISAR and stress gauges) indicate that the rise time of the shock front decreases with increasing shock strength, and increases with increasing mechanical impedance mismatch between layers; the strain rate at the shock front increases by about the square of the shock stress. Experimental and numerical results also show that due to interface scattering effect the shock wave velocity in periodically layered composites decreases. In some cases the shock velocity of a layered heterogeneous composite can be lower than that of either of its components.

INTRODUCTION

With high-performance heterogeneous materials such as fiber reinforced, woven composites and functionally graded materials finding increasing use in systems and structures designed to function in the severe shock environments, the assessment and evaluation of the response of those systems to complex loading conditions is essential. To do so, advanced computational methods relying on accurate physics-based material constitutive models are required, although such models cannot be correctly formulated without fully understanding the physical mechanisms of dissipation and dispersion of shock waves propagating in heterogeneous solids. Small-scale heterogeneity, e.g., grain boundaries in polycrystalline metals, fiber or particle reinforcement in polymer and metallic composites, could lead to scattering of waves[1], which could affect the rise time of a shock wave. The relative importance of scattering increases with the severity of the heterogeneity. Therefore, in order to obtain an accurate physically based constitutive relation to properly describe the dynamic response of heterogeneous materials and assess the performance of the composite material structures and systems in the shock related environments, it is critical to evaluate the role played by scattering induced by the heterogeneous microstructure as a shock wave propagates in the composite materials.

EXPERIMENTS

The structure of a periodically layered composite specimen[2] is shown in Fig. 1. It consists of two components in the form of thin disks that are alternatively stacked and bonded together using Hysol 0151 epoxy adhesive manufactured by Dexter Corporation. Hereafter, the component with larger mechanical impedance is called "hard" layer, while the other with lower mechanical impedance is called "soft" layer. The layered composite specimen is prepared by repeating the soft and hard layers alternatively as many times as necessary to form a specimen with the desired thickness.

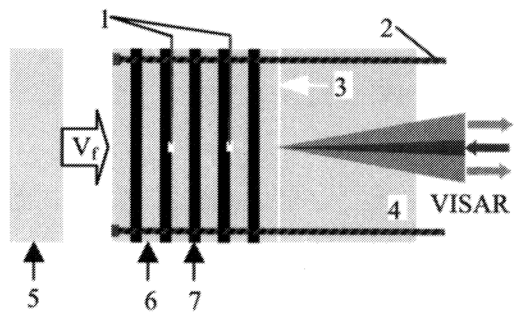

Figure 1. Schematic of shock compression experiment and specimen configuration.
1-manganin stress gauges; 2-charged electric pins; 3-mirror surface; 4-PMMA window; 5-flyer; 6-soft layer; 7-hard layer; V_f-flyer velocity.

The diameter of the disks is 38.1 mm. The soft layer material is a commercial polycarbonate (PC) supplied by McMaster--Carr. Two thicknesses of sheets, 0.74 mm and 0.37 mm, are used, which are denoted as PC74 and PC37, respectively. The hard layer material is one of the following: 0.37 mm thick 6061-T6 aluminum sheet (Al37), 0.37 mm or 0.19 mm thick 304 stainless steel sheets (SS37 or SS19), which are products of Allegheny Ludlum Co., 0.55 mm thick float glass (GS55), or 0.20 mm thick GS D-263 glass (GS20) disks from Erie Scientific Co. Three types of composites with five geometric configuration specimens, PC74/Al37, PC74/SS37, PC37/SS19, PC74/GS55 and PC37/GS20, are prepared and tested under planar impact loading. The window is a polymethyl methacrylate (PMMA) plate of thickness 12.7 mm. One of the window surfaces was aluminized to a mirror surface by sputtering aluminum in a vacuum chamber. A 0.74 mm PC buffer layer was used at the end of composite layers before the window layer is bonded. The mirror surface of the window contacts the buffer layer forming an internal mirror. The surfaces of all disks are well cleaned to achieve good bonding between interfaces. In order to uniformly spread the epoxy and reduce the thickness of the glue layer, a weight was placed on the assembled specimen to produce a stress of 50 MPa. The average thickness of the epoxy layer bond is about 20 μm. For the PC/Glass composites, the bonding layer can be as thin as 10 μm. The thickness of specimens is one of the following: 3.8 mm, 7.0 mm and 10.0 mm.

The flyers are 2.87 mm or 5.63 mm thick PC disks of 36 mm diameter, or 5.6 mm thick Al disks of 36 mm diameter in case higher shock pressures are desired. The flyers were accelerated to a desired velocity through a powder gun loading system located in the experimental Solid Mechanics facilities, Graduate Aeronautical Laboratories at Caltech (GALCIT). The bore of the gun is 36 mm, and the flyer velocity achieved by this gun ranges from 400 m/s to about 2,000 m/s. The flyer velocity is measured within 1% uncertainty by using a light interruption fiber optic system.

The particle velocity history on the interface between the window and the buffer layer was measured using a velocity interferometer, the so called VISAR system[3]. In order to capture the fine details of resonant oscillations of shock velocity profile resulting from the interactions between the incident shock wave and its multiple reflection waves from internal interfaces inside layered composites, a VISAR system with very high velocity resolution was constructed. The velocity fringe constant of this VISAR system is adjustable from 85 m/s/fringe to 1,500 m/s/fringe. Manganin gauges are also embedded between layers of some specimens to measure the stress history at selected internal points. Manganin gauges (50 ohms) produced by Dynasen Inc. and Micro Measurements Group were used in this study.

NUMERICAL SIMULATION

The finite element code, DYNA2D, was used to carry out axisymmetric two dimensional analysis of the shock compression of periodically layered composites loaded by planar impact (Fig. 1). The size of elements in the direction of wave propagation is about 130 μm and the aspect ratio of the elements was chosen to be as close to 1 as possible. The interface between layers was treated as a frictionless slide line. The increase in thickness of the specimen due to the adhesive bonding between layers is treated as an increase in the thickness of the PC layer since the physical and mechanical properties of the epoxy adhesive are very close to those of the PC. The standard DYNA2D artificial viscosity is used for all materials. During simulations, only glasses are treated as elastic material for the stress range of interest in this study[4]. For all other homogeneous PC, Al and SS components, PC or Al flyers, and PMMA window, Gruneisen equation-of-state and isotropic elastic plastic hydrodynamic constitutive relations were employed to model the response of individual materials.

RESULTS AND DISCUSSION

Experimental results indicate that periodically layered composites support steady structured shock waves[2]. With the increase of shock loading strength (pressure), the slope of the shock front increases. At the same time, the amplitude of oscillations in the wave profile also increases (Fig. 2). The larger the impedance mismatch between the components, the smaller the slope of the shock front, indicating larger dispersion (Fig. 3). When the interface density increases, the rise time of the shock front becomes shorter, indicating an increase in the nonlinearity property of the composite. Note, in the legend of Figs. 2 and 3, h and w are specimen and flyer thickness, respectively, V_f is flyer velocity and x is the distance from the impact face.

The experimental Hugoniots of PC/GS and PC/SS composites are compared with the predictions of Meyers[5] and Dremin's[6] mixture models, as well as 2-D numerical simulation results, in Figs. 4 and 5, respectively. It is seen that the shock velocity of a composite can be lower than that of either of its components. The calculated relations between the strain rate of the shock front and the shock stress for periodically layered composites are shown in Fig. 6. It is noted that for layered composites, the strain rate at the shock front increases by about the square of the shock stress, while in homogeneous media such as metals, the strain rate of the shock front increases by the fourth power of the shock stress[7], indicating much larger shock viscosity in the composites due to the scattering effect of interfaces on the shock wave.

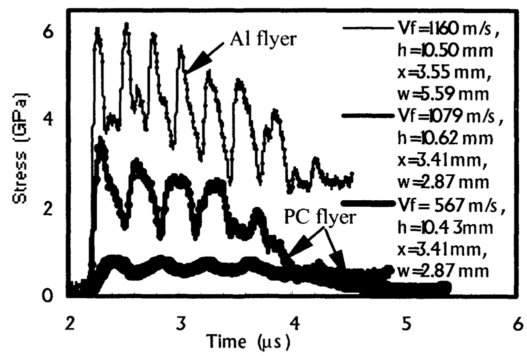

Figure 2. Influence of loading strength on measured shock stress profiles for PC74/GS55 composite.

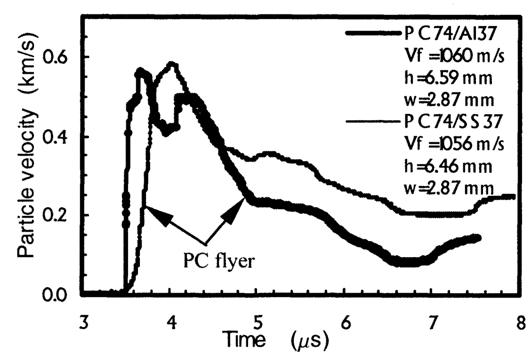

Figure 3. Influence of interface mechanical impedance mismatch of composites on measured shock particle velocity profiles.

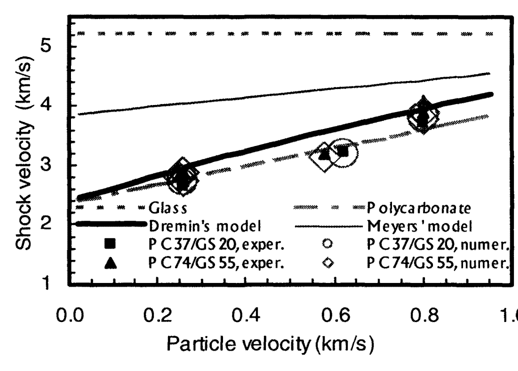

Figure 4. Comparison of PC/GS composite Hugoniots between experiments and predictions of mixture models and 2-D numerical simulations, and their homogeneous components.

Numerical analysis reveals that due to the interaction of multiple reflection of waves within the layers and the incident shock wave, i.e., the scattering of the shock wave due to interface, the pressure and particle velocity in the layered composites are not uniformly distributed during the shock compression, even if the steady shocked state is achieved. The pressure in the hard layer is lower, while the particle velocity is higher, in comparison to their corresponding values in the adjacent soft layer. The difference of pressures and particle velocities between the hard and soft layers and the amplitude of the resonant oscillations on the shock profiles, as well as the oscillation duration, are influenced by both the mismatch of their mechanical impedance and the geometric structure of the composite. Furthermore, the phases of velocity and pressure profiles of steady wave are not synchronous as they are in the homogeneous media[2].

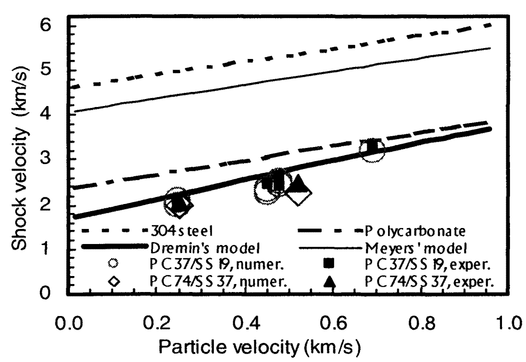

Figure 5. Comparison of PC/GS composite Hugoniots between experiments and predictions of mixture models and 2-D numerical simulations, and their homogeneous components.

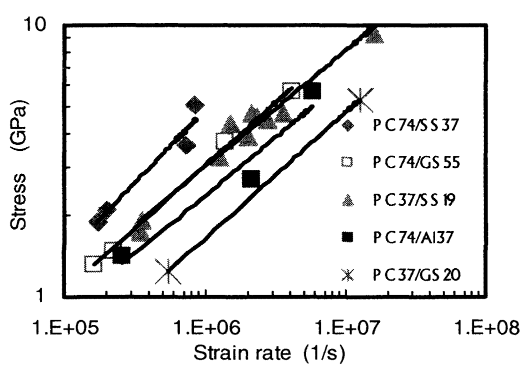

Figure 6. Shock stress vs. strain rate for the layered composite.

The influence of internal interfaces on shock wave propagation is through the scattering mechanism, i.e., multiple reflection of waves in the layers and their interaction with the shock wave. Due to interface scattering both the shock wave velocity (Figs. 4 and 5) and the shock front strain rate (Fig. 6) of the composites decrease. The decrease of shock front strain rate indicates a increase in the effective shock viscosity of the composites. Since ignoring the interface scattering effect the existing mixture models can only, at best, reasonably predict the response of the composites under strong shock loading conditions. In order to fully describe the response of a heterogeneous composite to shock compression loading, accurate physics-based constitutive relations need to be formulated taking into account the scattering effect induced by the heterogeneous microstructure.

ACKNOWLEDGMENTS

The research reported here was supported by the Solid Mechanics program at the Army Research Office (Dr. M. A. Zikry, Program Manager) and is gratefully acknowledged.

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