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Enhancing dynamic strength of diamond-SiC composite: Design and performance

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ABSTRACT

Diamond-SiC composite is a common hard material and its shock damage and failure is concerned particularly in armor devices. To enhance its shock strength, a novel microstructure design via modifying distribution patterns of diamond particles reinforced SiC matrix has been proposed and its performance has been evaluated via the computation of lattice-spring model. The effects of random, square, and triangle distribution patterns of diamond particles on the macroscopic shock response and the mesoscopic deformation feature of diamond-SiC composite has been explored systematically. The computation results demonstrate that the random and square distribution patterns of diamond particles lead to long-distance slip bands and stacking slip bands in the SiC matrix, respectively. Meanwhile, obvious damage of diamond particles is observed and the performance of composites against shock loading is deteriorated. In contrast, for the triangle distribution pattern of diamond particles, uniform and short-distance slip bands in the SiC matrix, therefore, damage of diamond particles is significantly reduced, which further gives rise to the high shock strength of composite. The present simulation results indicate that designing microstructures is an effective way to enhance macroscopic performance of diamond-SiC composite under shock loading.

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1. Introduction

The diamond-SiC (DSC) composite is known to have such properties as ultrahigh hardness, excellent wear resistance and low density, and is therefore an ideal choice as a material to be used in many industrial and armor applications [1–3]. It is typically fabricated using the liquid infiltration method under conditions of high pressure and high temperature (HPHT). SiC is used as a binding phase in the composite, and its high thermal stability makes the DSC composite more durable compared to other bonded diamond composites [4–5]. Diamond is a hard phase to enhance the strength of the DSC composite, because the Young's modulus of diamond is about two and half times greater than that of SiC. In the case of shock wave experiments, Salamone et al. [6] have indicated that the addition of diamond particles clearly increases the high strain rate impact resistance of the DSC composite. However, as the amount of diamond content increases, the dynamic strength of DSC composite decreases, due to the aggregation effect. It can be expected that, if the aggregation of diamond particles could be controlled and avoided, more addition of the diamond content and greater dynamic strength of DSC would be achieved.

Aggregation effect could be controlled by designing composite with subtle structure [7–10]. As an effort, nano-structured DSC composites have been synthesized at HPHT and demonstrated improvement of the fracture toughness [7]. On the other hand, development of additive manufacturing, e.g., three-dimensional (3D) printing, has been progressed rapidly in recent years, and specific microstructure could be prepared by such a printing even for composite materials [11–16]. In this paper, we propose a novel DSC composite structure design that can be implemented by 3D printing, which regulates the diamond particle distribution pattern in the SiC matrix to reduce the aggregation effect. In addition, for various diamond particle distribution patterns, it is of great theo-

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retical and practical significance to explore the dynamic strength of the DSC composite under shock wave compression.

To achieve this goal, we use the lattice-spring model (LSM) simulation to study the macroscopic shock response and the mesoscopic deformation feature of the DSC composite. Particular emphasis is put on the influence of the diamond particle distribution pattern on the dynamic strength of the composite. The micromechanism has been examined to reveal the relationship between the macroscopic response and the microstructure design. As a typical comparison, the results of three kinds of diamond particle distribution patterns (i.e., random, square and triangle) have been presented. The computation indicates that the triangle distribution is optimal among them in protecting the diamond particle, reducing the diamond damage and leading to a greater dynamic strength under harsh shock wave compression. Such a simulation and physical understanding provides new insights into the designing microstructure of DSC composites.

2. Design and simulation

The advanced rapid prototyping technology such as additive manufacturing are likely to enable the preparation of DSC composite with a designed diamond particle distribution pattern. Here we propose a novel way of the DSC composite structure design with different diamond particle distribution patterns in the SiC matrix, as shown in Fig. 1(a)–(c), i.e., the random, square and triangle distribution patterns, respectively. The diamond particles in the sample were generated by setting the particles in some specific regions, and all the diamond particles in this 2D model were set to be round. The diameter of a round diamond particle in all the samples is 20 μm. The diamond particle composition is ~50% in DSC composite. For the construction of the LSM simulation, the lattice was formed by points (of mass *m*), located in the lattice nodes, which interact through the springs. The model elements in LSM are not atoms but lattice points which represent small portions of the material. For diamond, the point mass is 1.833×10^{-12} g, and for SiC it is 1.676×10^{-12} g. The balanced distance of the points is 1 μm. The lattice points and springs form a network system representing the material, as illustrated by Fig. 1(d).

LSM, or discrete element method (DEM) [17–21], which has been developed extensively in recent years, can bypass various numerical difficulties resulting from displacement discontinuity. For example, LSM can successfully deal with fracture, fragmentation, and other dynamic damage processes. The nature of LSM is integration, rather than differentiation, for computation of the force on the lattice points. Between pairs of the adjacent lattice points, indexed by i and j, there are the central potential forces (f_{ij}^{n}) and the shear resistance forces (f_{ij}^{τ}). The interaction between the linked lattice points is represented by two springs, one is the normal spring for compression and tension and the other is the shear spring for shear and rotation, as illustrated in Fig. 2(a) and 2(b).

To simulate quantitatively the mechanical response of real materials, the selection of a spring stiffness coefficient is the key, because the springs in the lattice-spring model determines the interaction force, acceleration, stress, and fracture. Traditionally, the parameters used in calculating the interaction were usually given empirically and could only qualitatively represent the mechanical properties of the target materials. Here we use a quantitative method proposed by Gusev [22], which establishes a parameter mapping procedure between the FEM and the LSM that implement a conversion from the elastic moduli of the target material to the stiffness coefficients of the model springs. Firstly, this method constructs a finite element model that has the same mesh as the lattice-spring model. Secondly, the elastic constants of the target material are transformed into interaction parameters for the FEM (i.e., the stiffness matrix). Finally, using the same mesh, the interaction parameter conversion between the FEM and the LSM is performed. Based on the Gusev parameter mapping procedure, we established the two-dimensional (2D) network that equates with the FEM. Gusev [22] has validated the accuracy of LSM for various cell of periodic composite media. In our previous work, it also has shown that this method can represent the elastic properties of the dense brittle media quantitatively [23–24]. These results evidence the validity of LSM simulation. In the present work, based on the material parameters of SiC and diamond presented in Table 1, we have settled the parameters for the LSM simulation via the Gusev mapping procedure.

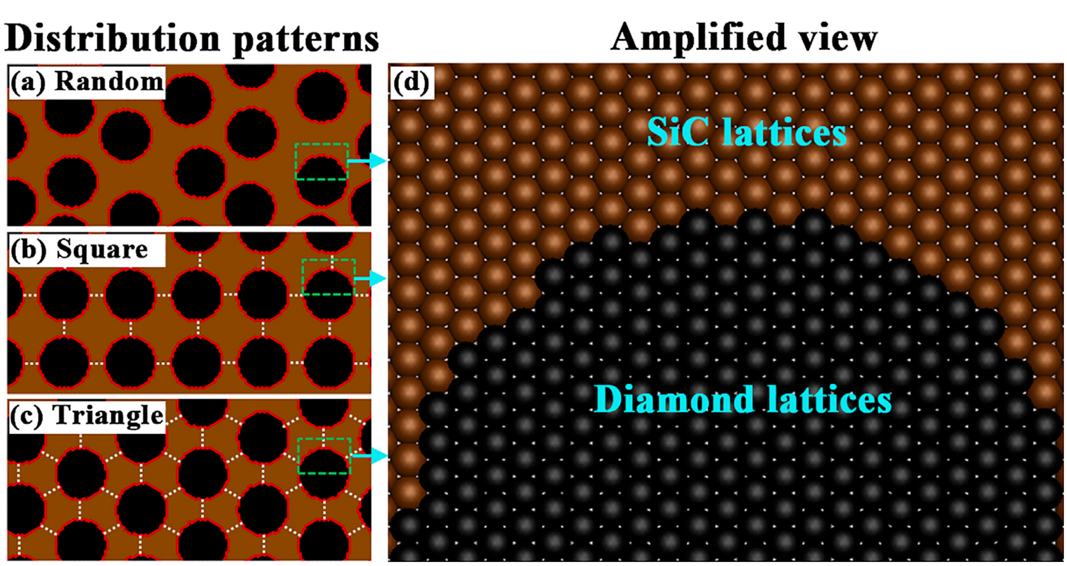

Fig. 1. Diamond particle distribution patterns in the DSC composite, (a) Random, (b) Square, (c) Triangle. The white dashed lines represent units of the regular diamond particle distribution patterns. The black areas represent diamond particles, and the nigger-brown areas are the SiC matrix. The red lines indicate the diamond-SiC interface. The magnified image in (d) shows the sample's details corresponding to the areas marked in (a)–(c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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