ENERGY DISSIPATION MECHANISM OF CERAMIC MATRIX COMPOSITES DURING THE PROCESS OF DWELL

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Keywords: Dwell; Ceramic matrix composites; Energy dissipation; Crack propagation; Stress wave dispersion

ABSTRACT

Ceramic matrix composites behave excellent ballistic performance in dwell process. With the purpose of increasing application value and revealing the ballistic mechanism of composites, it is necessary to investigate energy dissipation mechanism during the process of dwell. In this paper, the dwell process of SiC-Al ceramic matrix composites was studied by utilizing micro numerical simulation method. Micro and macro structure characteristics of composite are employed to analysis the behavior of ceramic phase and metal phase comparatively. The effect of composite microstructure on stress wave propagation is also investigated. It was concluded that the internal energy of ceramic phase or metal phase accounts for different proportion in the three different stages of dwell process. Ceramic and metal behave distinct performances. Crack initials and propagates in ceramic at the beginning till it encounters the metal. The plastic deformation of metal can prevent crack propagation effectively or change the crack propagation path, and also can create hydrostatic stress around the ceramic phase to enhance the full damaged strength, Resulting that the composite can bear higher strain and maintain intact to extend the dwell time. In addition, the interface between ceramics and metals can disperse and weaken the stress wave to reduce the energy.

1 INTRODUCTION

At the early stage of the bullet penetration the ceramic-metal targets, the projectile is defeated and its tip is blunted by the ceramic plate. which is named as dwell [1]. As an important phenomenon during the process of the bullet impacting on the lightweight ceramic and composite armours[2,3], dwell is closely related with the ballistic performances. Compared to common armour ceramics, 3D Interpenetrating phase ceramic matrix composites behaves excellent ballistic performance in dwell process [4], owing to its special energy dissipation mechanism. Because of the shortage of the effective experiment methods to obtain the information during the dwell process, this phenomenon cannot be captured easily, which restricts the application of dwell properties on armour protection design system.

Energy dissipated during dwell process reaches 845J in SiC-Al ceramic matrix composite, respectively increasing by 46.0%, 30.2% and 35.7% to the energy of B_4C, SiC and AD99 Al_2O_3 [4]. Highly energy dissipation in dwell process leads to the result that the composite express more excellent ballistic performance than ceramics. So it is important to investigate the energy dissipation mechanism, which can guide the armour structure design.

In this paper, macro and micro numerical simulation method is employed to investigate the different behaviours of the ceramic and metal phase in composites.

2 FINITE ELEMENT MODELING DESCRIPTION

The numerical tool used in this analysis was Ansys LS-DYNA 3D commercial hydro code. The model was shown in FIg.1(the left one), The target is composite tile of 6 mm thickness supported by a high strength steel of 5 mm thickness. In order to get the accurate stress state distributing in the ceramic titles, the Finite model was meshed finely. 3d CT scan images are used to generate the micro

numerical simulation model, as shown in Fig.1(the right one), which contains two phases about SiC and Al. The load extracted from the macro numerical simulation model is similar to the real service condition.

The bullet, back plate, Al phase are modelled with Johnson-cook model and the ceramic is modelled with Johnson_Holmquist_ceramic (JH2 model).

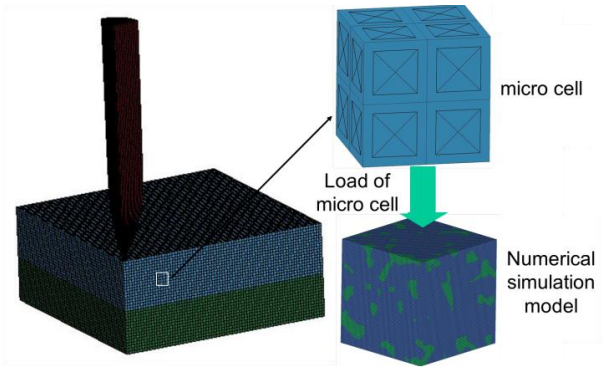


Fig.1: Schematic diagram of numerical simulation of composite micro region loaded proximal real service stress

3 DAMAGE ENERGY ANALYSIS OF COMPOSITE MATERIALS

The curve of internal energy with time changing is shown in Fig.2. When t≤2.0μs, there is no energy dissipation in composite, that is, the ceramic phase and metal phase in composite are zero. When 2.0μs < t≤9.7μs, there is a sharp rise of energy dissipation in 3 curves. In this stage, the energy is dissipated more in ceramic than that in metal. When t > 9.7μs, the total dissipation of composite descends as time goes on, and the dissipation of ceramic phase decreases significantly while that of metal phase ascents slowly with time increasing.

From Fig.2, we can get the energy dissipation ratio time curve of ceramic and metal phase, as is shown in Fig.3. In the different stages of dwell process, these two phases' dissipation ratio in total dissipation differs. When 2.0μs < t≤6μs, the metal energy dissipation ratio curve slows down. When 6.0μs < t≤9.7μs, although the ceramic energy dissipation is still in a dominant position, but the metal phase energy dissipation increases rapidly, the proportion of the increase over the previous stage has been greatly improved. When t > 9.7μs, ceramic energy dissipation decreased, energy dissipation of metal phase is dominant. In order to facilitate the research, such as the extraction of a 2D section of the 3D model shown in Fig.4 in the cross section, and marked the ceramic and metal phase, the change of damage and stress field evolution are discussed in the three stages of two phases behaviour influence on energy dissipation.

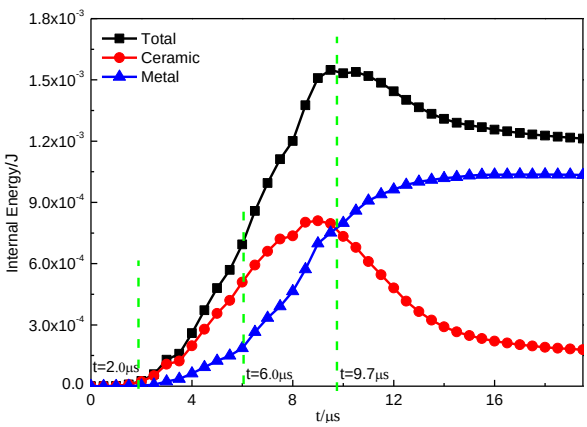


Fig.2 Internal energy~time of composite

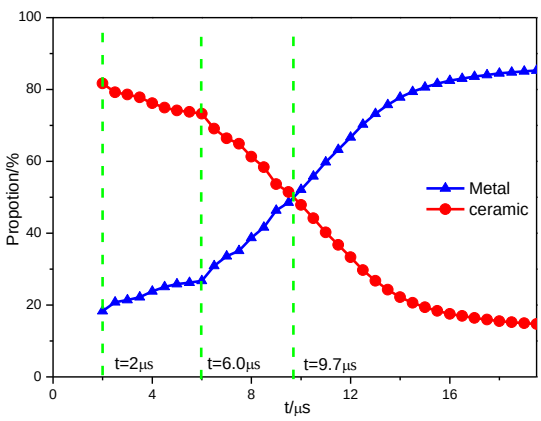


Fig.3 Ratio of internal energy~time curve

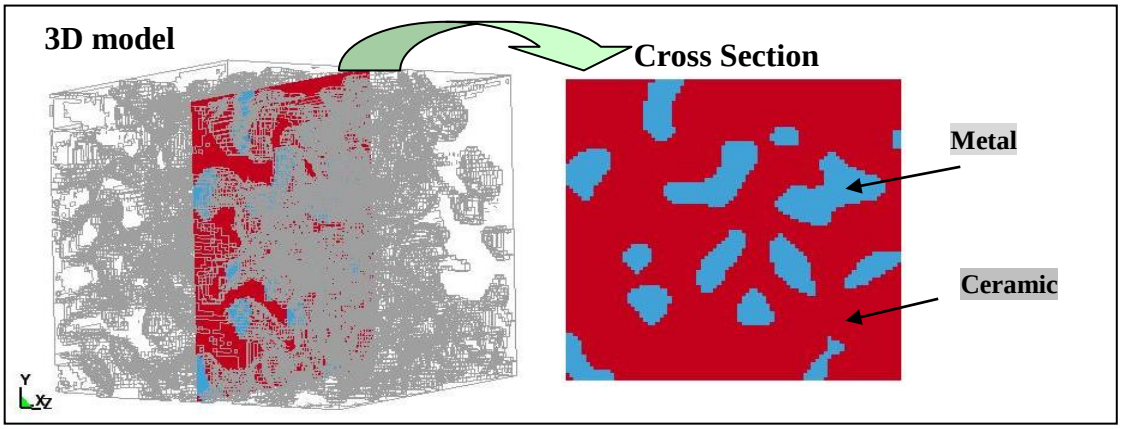
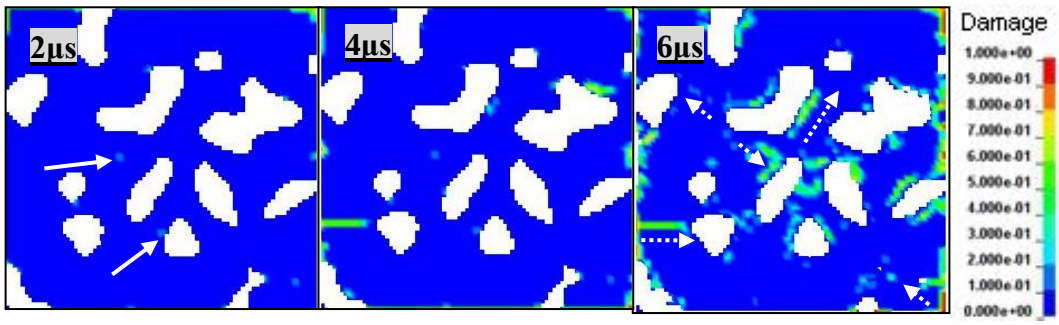


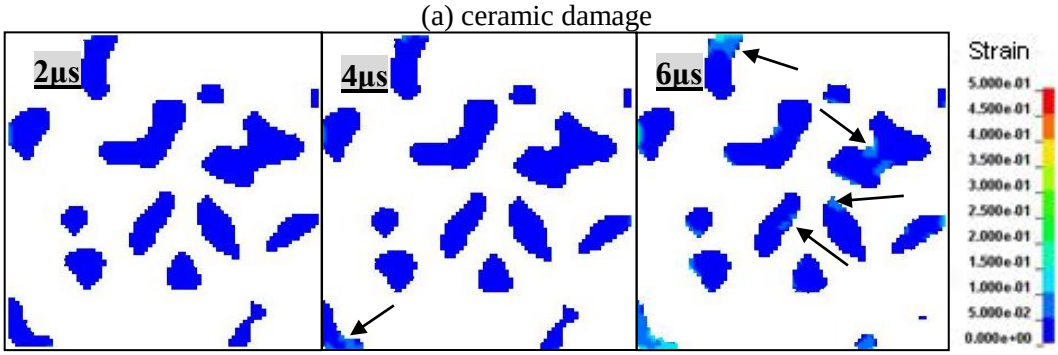
Fig.4 Cross section selection from 3D model

3.1 The initiation and propagation phases of micro cracks in ceramic phase（2.0μs＜t≤6.0μs）

From above analysis, when 2μs＜t≤ 6μs, ceramic dominates energy dissipation and the metal. Fig.5 shows ceramic phase damage and metal plastic strain distributions at the different time. when t=2μs, in the ceramic phase, near the ceramic and metal interface, damage generates, namely ceramic micro crack initiation, As shown by the solid arrow in the figure. Along with the time growth, early damage (micro crack) began to expand in ceramic phase or along the ceramic metal interface, as shown in the dotted arrow in the figure, at the same time some new damages produce. Fig. 6 shows the fracture surface of the recovery panel after the target test. The characteristics of the micro cracks in the ceramic phase and the expansion in the ceramic phase are shown. The characteristics are consistent with the simulated damage characteristics. From Fig.5 (b) of metal plastic strain distributions, when t ≤4.0μs, the metal phase almost has no plastic strain, until t=6.0 s, a small strain generates in the ceramic metal interface. In this process, energy dissipation of metal plastic deformation is lower. Therefore, in 2μs＜t≤ 6μs, energy dissipation is mainly in the form of ceramic panel damage and expansion, and lower in metal energy dissipation.



(a) ceramic damage



(b) metal plastic strain

Fig.5 Nephogram of ceramic damage and metal plastic strain at different times

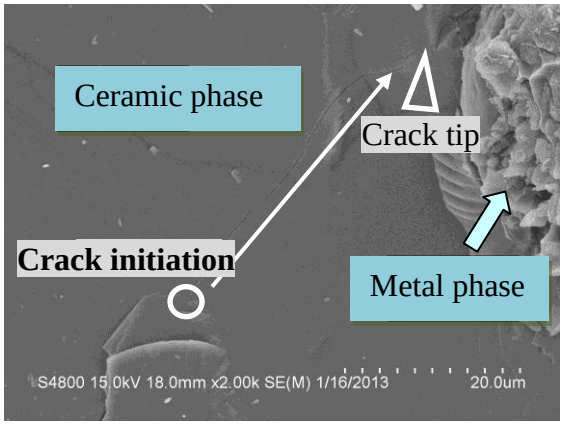
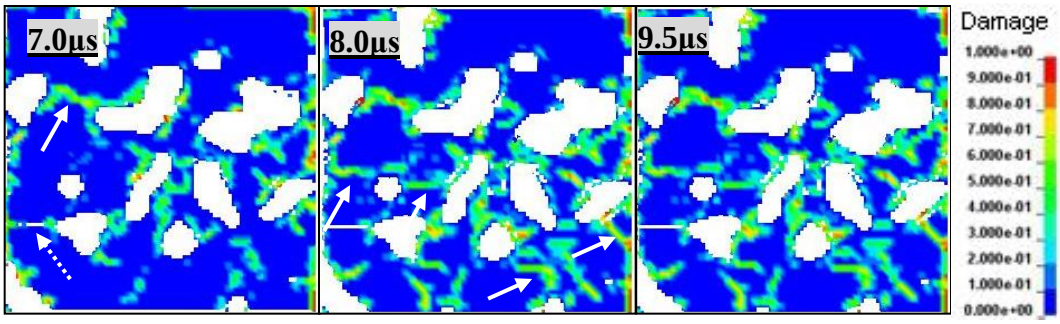


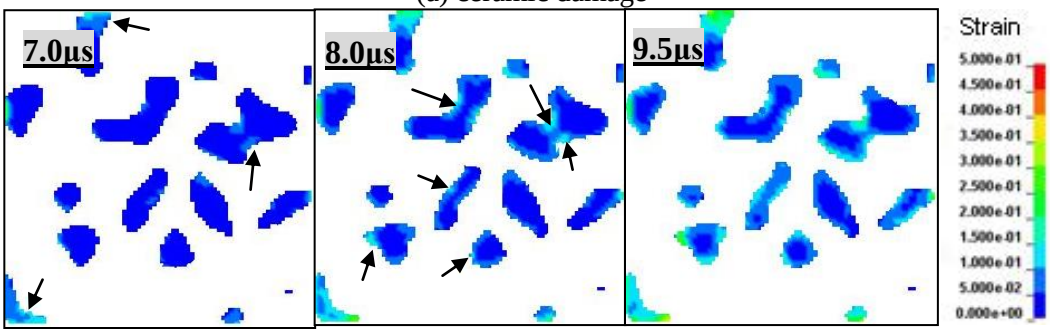
Fig.6 Micro crack initiation and growth in ceramic

3.2 Plastic deformation of metal phase and its confinement to ceramic phase (6.0μs < t≤9.8μs)

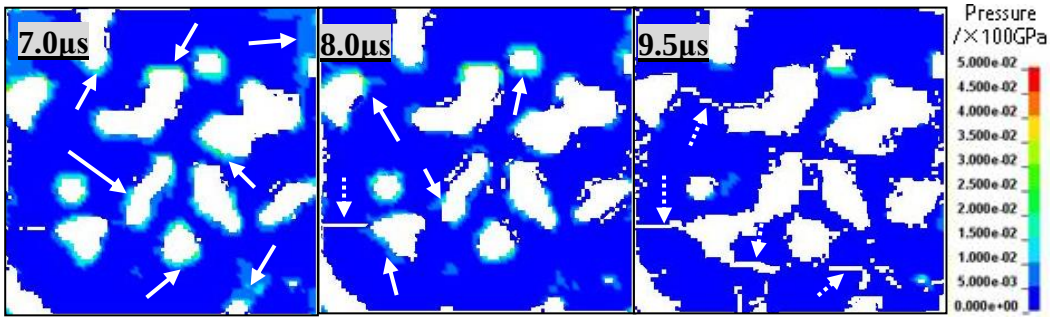
From above analysis, when 6.0μs < t≤9.8μs, although the ceramic energy dissipation is still dominant, but the rapid increase in the energy dissipation of the metal phase, the rate of increase than the previous stage has been greatly improved. In this process, the ceramic phase damage, the hydrostatic stress nephogram and the plastic strain nephogram of the metal phase are shown in Fig.7. From Fig.7 (a) in this stage, the damage generating in ceramic internally extends to ceramic metal interface, resulting in the interface damage also expands and connects mutually, as shown by the solid arrow in the figure. At the same time, a larger plastic deformation is produced in the metal phase at ceramic metal interface, as shown in Fig.7 (b) solid line arrow. The plastic deformation will restrict the ceramic metal. Fig.7 (c) is given by the ceramic phase under hydrostatic stress. It can be seen from the figure, in this stage, the plastic deformation of the metal phase stops the micro crack expansion or deflect extended path, bypassing the metal phase to continue to expand, as shown in the dotted arrow. Moreover, the confinement stress produced by metal plastic deformation can greatly improve the intact damage strength of ceramic and delay the ceramic damage.



(a) ceramic damage



(b) metal plastic strain

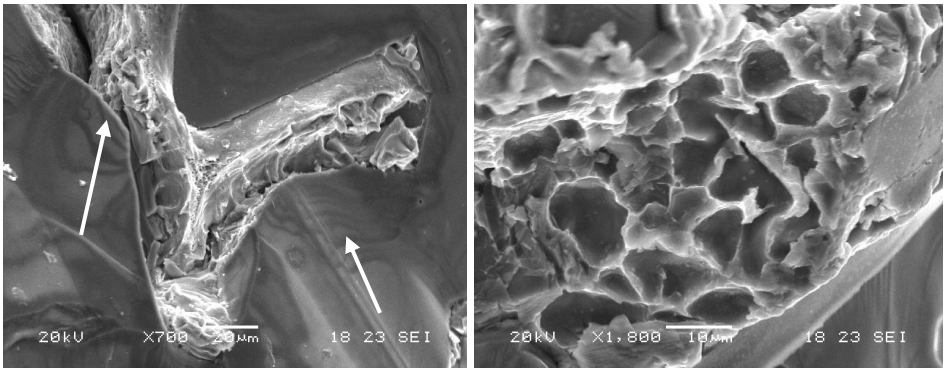


(c) hydrostatic stress in ceramic

Fig.7 Nephogram of ceramic damage, hydrostatic stress and metal plastic strain at different times

The fracture morphology of the recovery composite panel after the test is as shown in Fig.8. In the teared metal phase, at high magnification observation, there is a certain number of about 10 μm size of the dimples in the fracture metal. The metal phase exists certain plastic deformation. The plastic deformation of the metal phase influences the crack propagation process. An intact composite panel after impact is shown in Fig.9. When crack in ceramic phase propagates to the ceramic metal interface, it will be deflected to propagate along the interface, as shown in the black arrows in the figure, and the results are consistent with the above numerical simulation.

From the above analysis, when 6.0μs < t≤9.8μs, a large number of micro cracks in the ceramic phase extends to the interface, resulting in that the ceramic energy dissipation is still a large proportion, and in this process of metal plastic deformation increasing, the plastic deformation energy increases. At the same time, crack deflection and crack propagation also dissipate a lot of energy, resulting in metal phase energy dissipation showing a rapid increase trend.



(a) teared metal (b) dimples

Fig.8 Fracture appearance of composites

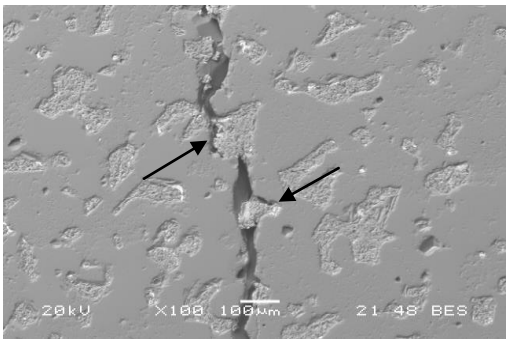
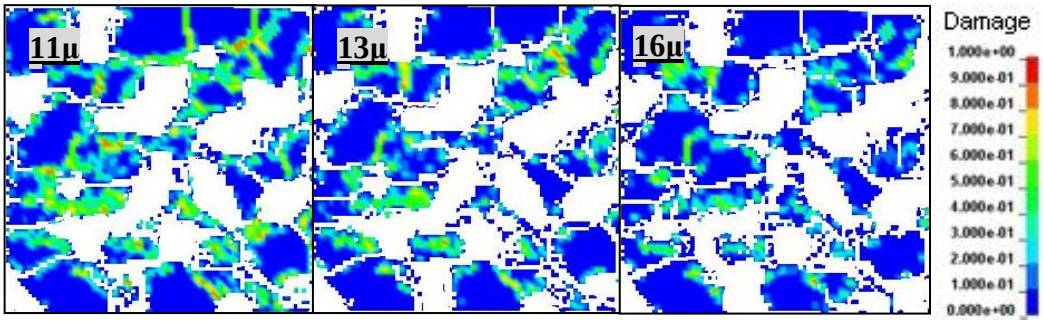


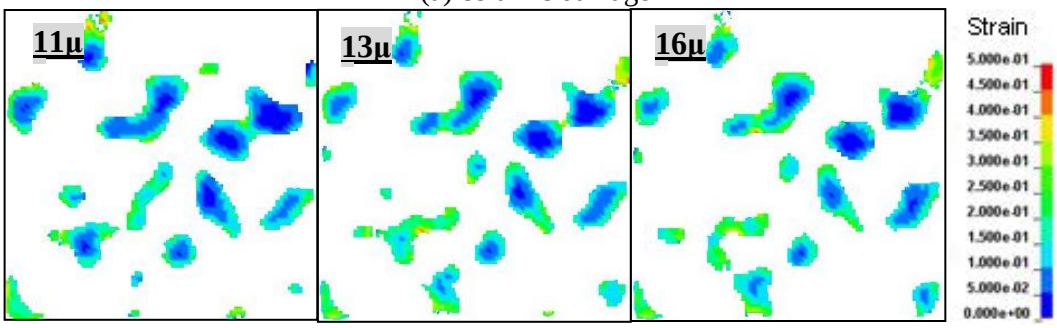
Fig.9 Crack propagation path in target

3.3 Metal plastic deformation constraint on ceramic fragments (9.5μs < t≤19.5μs)

As mentioned above, when 9.5μs < t≤19.5μs, the metal phase energy dissipation dominates, with a rapid decline of ceramic phase energy dissipation. Fig.10 shows the damage of the ceramic phase and the plastic strain nephogram of the metal phase. The ceramic in this process damaged seriously and is covered with crack as shown in Fig.10 (a). The metal phase produces large plastic deformation, which constricts the failure ceramic in order to maintain integrity. Fig.11 shows the morphology at different time in composite micro area. when 9.5μs < t≤15μs, although the ceramic has damaged seriously, but owing to the restriction effect of the metal phase, the overall composite material does not break into pieces. Until t=19.5 s, the composite material cannot afford the impact load, and the dwell process ends. In this stage, the ceramic energy dissipation is smaller after failure, while the plastic deformation energy dissipation of metal phase is dominant.

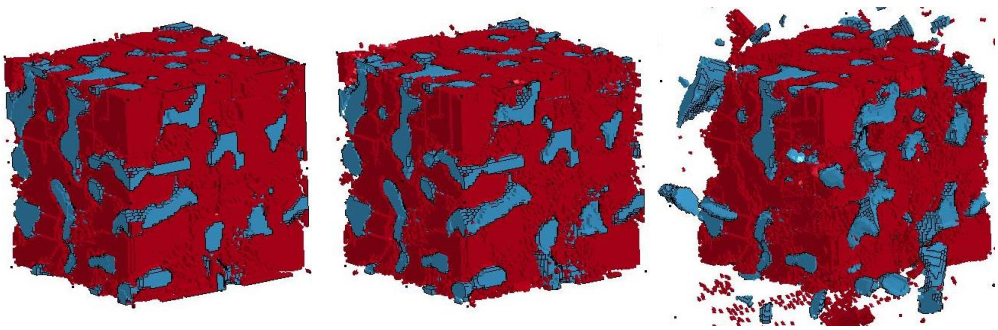


(a) ceramic damage



(b) metal plastic strain

Fig.10 Nephogram of ceramic damage, hydrostatic stress and metal plastic strain at different times



(a) t=12.0μs (b) t=15.0μs (c) t=19.5μs

Fig.11 Nephogram of ceramic damage, hydrostatic stress and metal plastic strain at different times

4 EFFECT OF CERAMIC METAL INTERFACE ON STRESS WAVE ATTENUATION

The special three-dimensional network structure of the composite produces a large number of ceramic and metal interfaces in the composite. The interface has a divergent effect on the stress wave, which makes the stress wave decay during propagation. For the attenuation of stress waves in composite materials, the material constructed by the numerical simulation model of two-dimensional

real microstructure is applied stress pulse on one side. The pulse amplitude is 150MPa and the length is 0.002 μs. Fig.12 shows the stress nephogram of the stress wave in the composite. when t=3ns, the stress wave propagates to the position ①, when the composite under a high stress level, about 120~150MPa. with the propagation of stress wave, when t=7ns, the stress wave spreads to the position ②, when the stress wave decreased to 90~120MPa. Then the stress wave continues to spread, when t=13ns, stress wave spread to the positions③, the stress decrease to only 30~60MPa. The average stress value with time curve of all elements in the same cross section at the three positions is as shown in Fig.13. It can be seen that the farther from the side applied stress pulse, the lower of the stress value. The stress wave disperses seriously, when the stress wave propagates along in the composite.

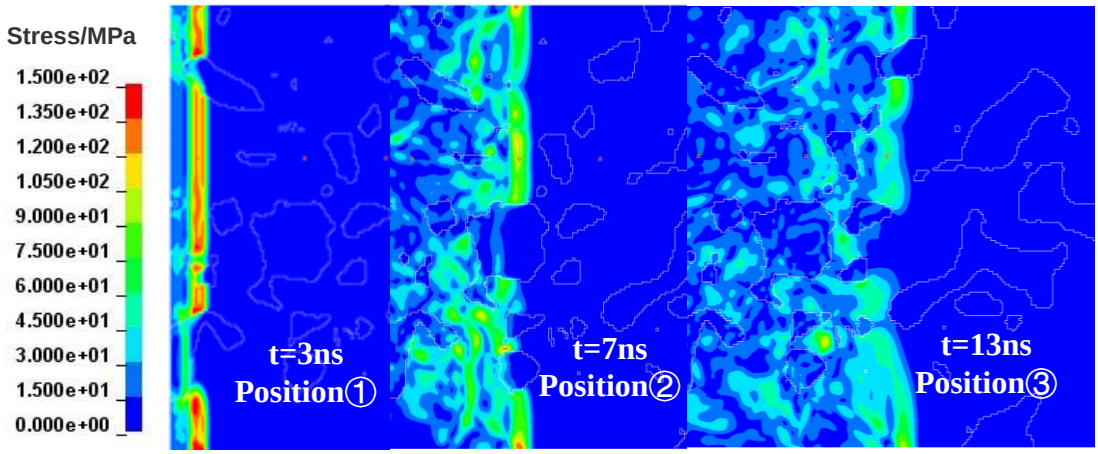


Fig.12 Stress nephogram of composite at different time

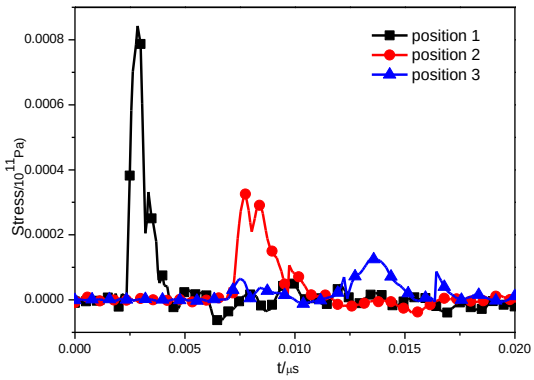


Fig.13 Average Stress~time curve in different position of composite

The ceramic metal interfaces play an important role in stress wave attenuation. The effect of micro interfaces on the stress wave is shown in Fig.14. Ceramic metal phase interface is arc, which can reflect and reflect the stress wave. the superposition degree of stress wave varies at different position in the composite, thus resulting in the stress concentration area in some areas of composite materials, such as the dashed arrows in Fig.14. Stress concentration can lead to larger energy dissipation. The stress wave propagation process in the metal phase is as shown in Fig.15. The maximum stress in the metal phase reaches 70MPa and the metal produce plastic deformation locally, which can reduce the stress wave energy.

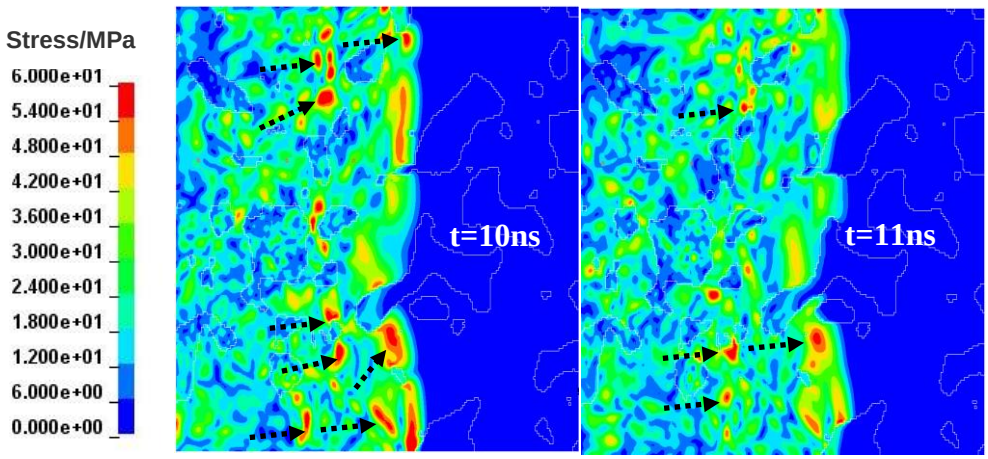


Fig.14 Stress nephogram at interface of ceramic and metal

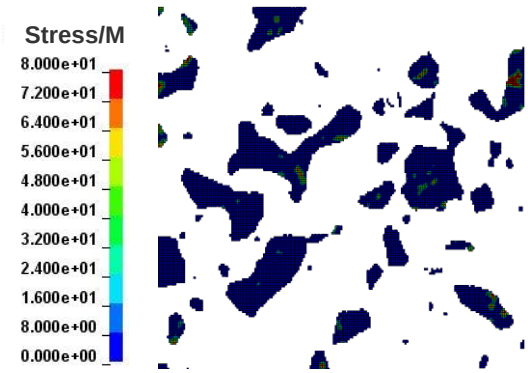


Fig.15 Stress nephogram in metal（Al）

5 CONCLUSION

The internal energy of ceramic phase or metal phase accounts for different proportion in the three different stages of dwell process. Ceramic and metal behave distinct performances. Crack initials and propagates in ceramic at the beginning till it encounters the metal. The plastic deformation of metal can prevent crack propagation effectively or change the crack propagation path, and also can create hydrostatic stress around the ceramic phase to enhance the full damaged strength, Resulting that the composite can bear higher strain and maintain intact to extend the dwell time. In addition, the interface between ceramics and metals can disperse and weaken the stress wave to reduce the energy.

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