Research on Damage Mode of Super-high Temperature Composite Ceramic with Boride Base

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Abstract. Because of the space experiments of various countries, there are so many small pieces of debris in space, leading to the accident of spacecraft. Through AUTODYN software numerical analysis and SPH method, a numerical simulation study was carried out on the failure mode of the cylinder projectile impacting the double-layer ceramic target plate of aluminum alloy and boride base superhigh temperature composite ceramic at ultra high speed. The variation of perforation radius of the projectile against double target plate was obtained. The paper concludes that, in the failure mode of different mass projectiles striking double target plate, the total perforation radius of the second layer boride base superhigh temperature composite ceramic target increases first, then decreases and finally explodes.

1. Introduction

With today's rapid development of science and technology and increasingly fierce competition for space among countries around the world, the spacecraft is an important equipment in the field of space research, so the satellites and the space shuttle have become a top priority. The Schenberger used one-dimensional shock wave theory to explain ultra-high speed impact and simplified the model into one-dimensional problem. When the collision speed exceeds 10km/s, the material will melt and vaporize, which requires in-depth study on the protection performance and the mechanism of melting and vaporization [1]. R.L.Bjork studied the mechanism of shock wave heating involved in material melting and vaporization under ultra-high speed collision. It is concluded that the melting and vaporization of the material are related to the residual specific energy of the material after shock compression and other state unloading [2]. Guo Xiaojun studied the mechanism of drilling explosive cracking of brittle materials [3]. Li Yanwei investigated the mechanical properties of the composite sandwich structures by theoretical, numerical and experimental methods [4]. However, it is very difficult to use a theoretical model to study the ultra-high speed impacting. At the present stage, only some physical parameters can be estimated, but it is difficult to give various thermodynamic states concerned in the process of the speed impacting of ultra high. Therefore, the study of ultra-high speed collision also needs to rely on experimental research and numerical simulations.
2. The method of numerical simulation

2.1 The technique of numerical simulation

Numerical simulation is the using of computers to simulate experiments. The experimental results are obtained by simulating various possible situations. From solving the influence of single variable on experiment at the beginning, PEBI grid has been developed, and now the integrated simulation technology has been mainly developed to conduct quantitative attribute uncertainty analysis. Quantitative analysis of attribute uncertainty will affect the calculation results. The first step: The differential equations and corresponding definite solution conditions are established to reflect the problems; The second step: Search for efficient and accurate calculation methods. It includes the discretization method of differential equation, the solution method, the establishment of coordinates and the treatment of boundary conditions; The third step: Program to calculate. Because the actual problem is complicated, the model will be more complicated nonlinear equation, the numerical solution to the practical problems in the theoretical research on the beginning of the may not be perfect, so need to go through a large amount of experimental verification; The fourth step: The data results are obtained and a large amount of data of numerical simulation is displayed by Numbers, tables, images, etc.[6].

2.2 Calculation method

SPH method was chosen for the calculation of high-speed impact numerical model of boride base super-high temperature composite ceramics. SPH method is a meshless Lagrange method. The basic idea is to transform the motion of matter into the interaction of particle. In principle, mechanical processes can be described accurately as long as there are enough mass points, and various physical quantities (mass, velocity, etc.) can be carried on each material point. By solving the kinetic equation of the particle group and tracking the motion orbit of each particle group, the mechanical behavior of the whole system is obtained. The algorithm of SPH method is that the SPH particle has a unique interpolation point corresponding to it. The SPH particle is calculated by interpolation, and the solution of each interpolation function is solved respectively, so as to find the solution of the whole problem.

Though the method of Lagrange has the advantage of fast calculation and material interface clear, to simulate the material damage and fracture process, but when it comes to material, the large deformation may cause distortion grid distortion and reduce calculation accuracy; ALE method is a coupling calculation method of Lagrange and Euler, to some extent, the shortcomings of Euler and Lagrange methods can be overcome, but it also needs to solve the problems of hybrid grid computing effectively; SPH is a kind of typical meshless though Lagrange numerical method. This method does not need grid, suits to describe the large deformation problem, but on the SPH method in the stability of the algorithm, the simulation precision aspects need to be further improved. Euler is usually used to simulate large deformation flow problems. The numerical methods used in the numerical simulation of 10km/s impact velocity at ultra-high speed are mostly Euler methods, and Euler's method is very useful for computing the fragmentation cloud formation process. For example, the CTH program. However, the Euler method needs to focus on material interface treatment, material transportation and material breakage. The SPH method can avoid the interface problems between Euler mesh and materials. Therefore, it is especially suitable for solving dynamic large deformation problems such as high-speed collision. Although the precision of the solution also depends on the arrangement of the particle points, the requirement of the lattice arrangement is much lower than that of the grid. Because there is no grid relation between the particle and particle, it can avoid the precision damage caused by grid distortion in extreme large deformation. In addition, it can handle the interface of different media more conveniently. $A(r)$ is between particle i and its adjacent position j, the mathematical expression formula of SPH is:
\[ \frac{d\rho_i}{dt} = m_i \sum_j u_{ij} \cdot \delta_{ij} W_{ij} \] 
(1)

\[ \frac{du_i^\alpha}{dt} = -\sum_j m_j \left( \frac{\sigma_i^{\alpha\beta}}{\rho_i} + \frac{\sigma_j^{\alpha\beta}}{\rho_j} + \Pi_{ij} \right) W_{ij,\beta} \] 
(2)

\[ \frac{dE_i}{dt} = \sum_j m_j \left( u_{ij}^\alpha - u_j^\alpha \right) \left( \frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{l}{2} \Pi_{ij} \right) W_{ij,\beta} + H_i. \] 
(3)

Among them, \( A(r) \) is the macroscopic value at any position \( r \) in space, \( \rho \) is the density of the particle, \( m \) is the mass of the particle, \( u^\alpha \) is the velocity component of the particle, \( \sigma^{\alpha\beta} \) is the stress tensor of the particle, \( E \) is the specific internal energy, \( \Pi \) is artificial viscous pressure, \( H \) is artificial heat flow.

3. Model building

3.1 Geometric modeling

![Fig1. Geometric model diagram of high-speed impact on double-deck plates](image)

Using AUTODYN software simulates projectile radius for \( r_0 \) length of \( d \). First, a 2A12 aluminum alloy plate with a square length of 40mm and a thickness of 1mm is hit directly, there will be a cloud of debris. After a certain interval \( d_0 \), the debris cloud impacts the pattern of a 40mm square, and the thickness of the boron, and the impact pattern of the ceramic plate(\( ZrB_2 - 30SiC \)). Under normal circumstances, Lagrange method should be adopted for metal materials used as target plates. Because the calculation time of double plate model is too long, 2A12 aluminum alloy plate is metal material, so choose SPH.SPH method was used for brittle ceramic plates, the modeling of projectile and target plate adopts two-dimensional axial symmetry method. The number of particles is 20 per millimeter(In the figure below, the projectile radius is 1.5mm, the length is 3mm, and the target plate thickness is 2mm). Because the double plate hit the model too long, in order to observe the final size of the perforation radius, the time is set long enough, and the increment is set to 0.001. In order to improve the calculation accuracy, although the energy error will be large, the result of perforation radius caused by the projectile in the model is still convincing enough.

3.2 Debris cloud model
Analysis on the failure mode of the projectile hitting the double layer target plate of aluminum alloy and composite ceramic, that is, there is a gap in the double plate structure. Let the aluminum plate withstand the high-speed impact of the projectile, forming a debris cloud. The failure mode of boride base super-high temperature composite ceramic materials subjected to high-speed impact of debris cloud was examined.

![Fig2. Schematic diagram of Swift debris cloud model](image)

![Fig3. Schematic diagram of Piekutowski debris cloud model](image)

![Fig4. Diagram of the Bless fragmentation cloud model](image)

Figure2 shows the Swift fragment cloud model, Swift hypothesizes that the debris cloud forms an expanding shell. The fractal cloud is uniformly distributed on the spherical shell. The movement of debris clouds is decomposed into the linear motion of the center of mass along the trajectory direction and the expansion movement centering on the center of mass. Figure 3 shows the Piekutowski debris cloud model, the solid line represents the debris cloud, and the dotted line represents the outline of the debris cloud. Figure 4 shows the Bless fragmentation cloud model, each shaded area in the figure refers to a layer fissure. Through a lot of numerical simulation results can be seen, the fractal cloud model of Piekutowski is most similar to that of the fractal cloud in numerical simulation.

### 4. Failure modes of projectiles with different mass striking double target plates

In the study on the failure mode of different mass projectiles striking double target plates, the spacing between the two plates is 50mm, the impact speed is 4km/s, and the thickness of the first aluminum plate is 1mm. The thickness of the second layer composite ceramic target plate of $\text{ZrB}_2 - 3\text{SiC}$ is 2mm. Debris cloud impact boride base ultra high temperature composite ceramic target board does not involve a longitudinal crack, longitudinal cracks may occur only if the collision fails. Because the longitudinal crack is the damage near the breakdown. The size of projectile changes, and the quality of projectile changes accordingly. The projectile with a radius of 1mm and a length of 3mm is written as: 1-3 projectile, and so on.

The lateral displacement of the target plate around the hole is the deformation displacement caused by the phase around the hole to the fixed end of the target plate. As can be seen from table 1, in a certain range, with the increase of projectiles, the lateral displacement of boride base ultra-high temperature composite ceramic target plate around the hole is also larger. The reason is that the greater the quality of the projectile, the greater the quality of the remaining fragments, the more kinetic energy it has, the more transverse strain energy is given to the target plate, the deformation displacement of the target plate is also larger.

| Parameter                  | 1-2  | 1-3  | 1.5-3 | 1.5-4 | 2-4  |
|----------------------------|------|------|-------|-------|------|
| Projectile (mm)            |      |      |       |       |      |
| Perforation radius of aluminum | 2.7839 | 2.8103 | 3.8691 | 3.9383 | 4.4027 |
Table 1 shows the detailed data of damage caused by projectiles of different mass hitting double-layer target plates, but it involves many parameters and is not easy to be compared, so it is simplified as table 2.

Table 2 shows that, projectile impacting in different quality double target plate failure mode, aluminum plate punch radius increases with the increase of quality of the projectile; However, the total perforation radius of the second layer boride base ultra-high temperature composite ceramic target plate increases first, then decreases, and finally explodes. And just to be clear, graph the data in table 2, as shown in figure 5.

| Number | Projectile (mm) | Perforation radius of aluminum plate(mm) | Total perforation radius of ceramic plate(mm) |
|--------|----------------|-----------------------------------------|---------------------------------------------|
| 1      | 1-2            | 2.7839                                  | No breakdown                                |
| 2      | 1-3            | 2.8103                                  | 2.6560                                      |
| 3      | 1.5-3          | 3.8691                                  | 1.5550                                      |
Fig5. The relation diagram of perforation radius of projectiles with different mass hitting double-layer target plate

As you can see from figure 5, the 1-2 projectile did not break through the target plate at the beginning. The curve first increased because the projectile became larger, the remaining projectile fragments increased, and the perforation radius of the remaining projectile fragments against the ceramic plate also increased. The reason for the decrease is that in the case of small projectiles, the remaining projectile fragments are torn through the target plate. The projectile size continues to increase. Residual projectile fragment size continues to increase. The perforation mode of the target plate becomes penetrating. The total perforation radius of boride base ultra-high temperature composite ceramic target plate will be decreased. When the size of projectile continues to increase to a certain extent, and the remaining fragment size of projectile also continues to increase to a certain extent, the resulting debris cloud has a much larger mass, and there are particles in it that can damage the target plate. So the perforation diameter of the target plate is not determined by the residual projectile fragments, but by the particles in the debris cloud. The perforation diameter will increase explosively. That is, from 4.0301mm perforation radius of 1.5-4 projectiles to 14.542mm perforation radius of 2-4 projectiles. In the failure mode of projectiles with different mass hitting target plate, only projectile size is variable. The projectiles with dimensions 1-2, 1-3, 1.5-3, 1.5-4 and 2-4 were selected respectively. The failure modes of projectiles with different mass hitting double-layer target plates are shown in FIG. 6.

| Projectile (mm) | Overall failure condition | Failure of ceramic target plate |
|----------------|--------------------------|--------------------------------|
| 1-2            |                          |                                |

| 1-2            | 1-2 1-3 1.5-3 1.5-4 2-4 | 4.0301 3.9383 4.4027 14.542 |

- Total perforation radius of ceramic plate (mm)
- Perforation radius of aluminum plate (mm)
Fig 6. Damage model diagram of projectiles of different mass hitting double-layer target plate.

Fig 7. Damage diagram of projectile 1.5-4 impact the second layer target plate.

Fig 8. Damage diagram of projectile 2-4 impact the second layer target plate.
When the quality of the projectile is higher, the shard cloud from the projectile passing through the aluminum plate is larger. Impact the boride base superhigh temperature composite ceramic target plate, it will appear in figure 7 of 1.5-4 projectile with numerical simulation boride base ultra high temperature composite ceramic target plate damage and the details of the figure 8 in 2-4 projectile numerical simulation boride base ultra high temperature composite ceramic target board the details of the damage, 1.5-4 projectile and 2-4 projectile target plate breakdown damage and close to the center of the target plate all broken. The puncture radius of 1.5-4 projectile is 4.0301. The puncture radius of projectile is 14.542. This indicates that the energy of the debris cloud shock wave reaches the strain energy required for the damage of the target plate and the bigger the pellets, the bigger the radius of the target plate. Although the debris cloud produced by 1-3 projectiles and 1.5-3 projectiles did not break through the boride base ultra-high temperature composite ceramic target plate, it caused central perforation in the center of the target plate. When the size of the pellets went down to a radius of 1mm, with a bullet of 2mm, the target board only had a crater, and no center piercings.

5. Conclusion
In the failure mode of different mass projectiles striking double target plates, the total perforation radius of the second layer boride base super-high temperature composite ceramic target increases first, then decreases and finally explodes. The explosive growth is due to the fact that the cloud of debris is much more massive. This time, there are particles in the debris cloud that can destroy the target. The perforation diameter of the target plate is not determined by the residual projectile fragments, but by the particles in the debris cloud, so the perforation diameter will increase explosively.

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