NUMERICAL SIMULATION OF HYPERVELOCITY IMPACTS ON ALUMINUM MESH

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ABSTRACT:

To study the behavior of mesh bumper under hypervelocity impact, numerical simulation of aluminum projectile impacting on aluminum mesh has been carried out. Two kinds of cross wired aluminum mesh are considered, which are different in wire diameter and mesh size, and the simulated impact velocities range from 3km/s to 6km/s. The simulation results show that the debris produced by the impact is consist of some fragments clusters, some particles in the fragment clusters have higher velocities than the initial impact velocity, which leads to localized energy concentration. The velocity ratio (residual velocity/initial projectile velocity) increases while projectile velocity increases, same relation exist between the ratio of fragment dispersing velocity/projectile velocity and projectile velocity. It is concluded that single aluminum mesh has good ability of breaking up and dispersing projectile.

AL ——Aluminum
d_w ——AL wire diameter
R ——Arc radius
L ——Distance between wires
ρ ——Density of AL
ρ_A ——Area density
$m_{p\text{-}up}$ ——Mass of uprange fragments from projectile
$m_{t\text{-}up}$ ——Mass of uprange fragments from target
$m_{t\text{-}down}$ ——Mass of downrange fragments from target
$V_{p\text{-}down\text{-}z}$ ——Normalized average axial velocity of downrange fragments from projectile
$V_{p\text{-}down\text{-}x}$ ——Normalized average tangential velocity of down range fragments from projectile
V_{impact} —— impact velocity

1 INTRODUCTION

The M/OD (Meteoroid and Orbital Debris) in the outer space of earth is a threat to the spacecraft survivability and crew safety primarily because of the potentially high-impact speeds and energy involved in collisions between spacecraft and M/OD. Today's M/OD shields are basically Whipple shield or multi-shock shield, the principle is to use one or several sacrificial bumpers to disrupt the impactor and disperse the fragments, thus the impactor momentum is distributed over a wide area of the real wall, which will reduce the damage level. The bumper could be continuous or discontinuous, metal mesh is a good candidate of discontinuous bumper. Since 1990s, JSC, NASA has carried out series of experiments on metal mesh bumper[1][2][3][4], based on which some M/OD shield structure has been developed. However, compare to continuous bumper, the research on mesh bumper is still insufficient.

Aluminum alloy with low density and high strength is a material commonly used in spacecraft. This paper takes a numerical simulation approach to study the behavior of AL mesh under hypervelocity impact.

The numerical hydrocode used in this study is LS-DYNA 3D with its SPH processor. SPH method is a meshless Lagrangian method, which has great advantage in hypervelocity impact field. Compared with the Lagrangian method, SPH method overcomes the instability caused by the large displacement and large distortion; compared with Euler method, SPH method can provide a clear interface between different materials. The reliability of SPH method in simulating hypervelocity impact between metals has been proved by many real tests. CARDC, HAI has carried out series of test on traditional shield, such as Whipple shield and multi-shock shield, and series of numerical simulation analyze work has been done, which according well with the test[5][6][7].

2 NUMERICAL SIMULATION METHOD

2.1 SPH Particle Model of AL mesh

AL mesh referred in this paper is cross wired AL mesh as shown in Fig. 1. To specify the mesh two parameters are needed, which are wire diameter d_w and grid side length L (distance between two adjacent wires).

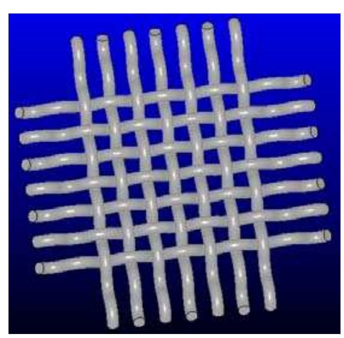

Fig 1. Cross wired AL mesh

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As the structure of a cross wired mesh is too complicated to be modeled by using Finite element modeling software, a c++ program is written to generate the SPH particle model of AL mesh. The shape of the aluminum wire in the mesh is mostly like a sine curve. To make the modeling work easier, it is assumed that the shape of the wire is made up by arcs, which has a chord length L and a height $d_w/2$ as show in Fig. 2.

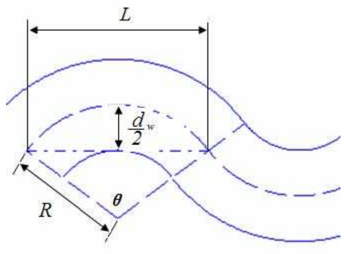


Fig 2. wire of AL mesh

The arc radius R and central angle θ can be determined.

$$R = \frac{L^2}{4d_w} + \frac{d_w}{4} \tag{1}$$

$$\theta = 4a\tan(d_w / L) \tag{2}$$

Then the area density of the mesh ρ_A can be obtained:

$$\rho_A = \frac{\rho}{L^2}\int_{-d_w/2}^{d_w/2} \frac{\theta}{2\pi}\cdot\pi((R+\sqrt{(d_w/2)^2-y^2})^2 - (R-\sqrt{(d_w/2)^2-y^2})^2)dy \tag{3}$$

Where ρ is the density of aluminum.

To ensure the stability of the simulation, a uniform particle model is needed, which means each particle in the model has the same volume and the same mass. Under the assumption above, the whole model can be finished in two steps. First, construct the model of a single aluminum wire, then implement copy, translate, rotate, and reflect operation to make up the whole mesh as shown in Fig. 3. A half model is used to reduce the computational time.

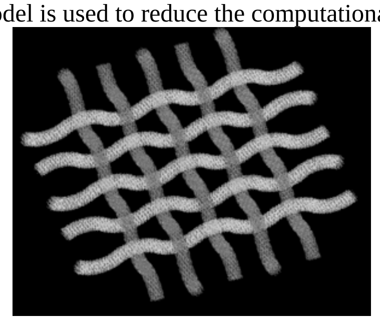


Fig 3. SPH particle model of AL mesh

2.2 Material Model and Equation of State

Because of the extremely high temperature and extremely high pressure, the behavior of material under hypervelocity impact is complicated. The thermal effect is much more obvious than that under low velocity impact. Therefore, an Equation of State is needed to describe the relation between pressure, density and internal energy, and the compress effect and irreversible thermal process as well. Mie-Gruneisen equation is a common used equation, which can describe the thermal behavior of most solid metal. The EOS_GRUNEISEN keyword of LS-DYNA is selected for the aluminum projectile and the AL mesh.

The commonly used material models in hypervelocity impact field are Elastic-Plastic-Hydro model, Johnson-Cook model and Steinberg-Guinan model, the last two models considered the relation between yield strength and temperature. In Johnson-Cook model the yield strength reduces as the temperature rises, while in Steinberg-Guinan model the strength is set to zero when the melting temperature is reached, thus just below the melting temperature the material can have high strength. Therefore, the Johnson-Cook model is chosen.

2.3 Consideration on Simulation Matrix

To study the behavior of AL mesh under hypervelocity impact, the following aspect was considered.

1. Difference between AL mesh and aluminum plate;
2. Different mesh parameters;
3. Varied projectile diameters;
4. Varied impacting velocities.

According to the combination of the projectile and the target, five groups of simulation are set. The simulated impact velocities are 3km/s, 4km/s, 5km/s and 6km/s in each group. Both the target and the projectile are Al 2024-T4. The target of the first group is Al plate, the rest are Al meshes. The detail parameters are show in table 1. Among all the groups the target plane is XY plane, and the projectile flies in the direction of -Z axis.

Table 1. Simulation parameters

Group No	d_p	d_w	L	ρ_A
Group 1	1.5	N/A(plate)	N/A(plate)	0.030
Group 2	1.5	0.23	0.51	0.030
Group 3	1.5	0.3	0.85	0.051
Group 4	2.38	0.3	0.85	0.051
Group 5	3.18	0.3	0.85	0.051

3 RESULTS AND DISCUSSION

3.1 Fragments Distribution

The fragments are consisting of uprange fragments and downrange fragments, as shown in Fig. 4. The downrange fragments include debris bubble, main fragments of the projectile, and fragments clusters. The number of the fragments cluster is approximately the number of grids encountered by projectile during the impacting process, the position is consistent as well. Most particles in the fragments cluster have a higher velocity than the main fragments of the projectile. Some particles in fragments cluster even have a higher velocity than the initial impact velocity. Among all the fragments clusters, those clusters near the impact center have the highest velocity, while those far from the impact center have higher dispersing velocity (velocity at XY plane). When the impact velocity is relatively low, the projectile is broken up into several big fragments and some small fragments, just like it is cut by the mesh. However, as the impact velocity rise, the big fragments begin to broken up into smaller fragments.

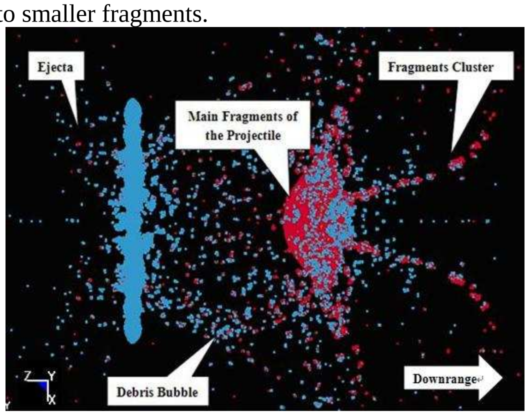


Fig 4. Impact Fragments Distribution

Compared with AL mesh, aluminum plate with the same area density has a bad performance on disrupting the projectile and dispersing the fragments. At low impact velocity (3km/s or 4km/s), the projectile can't be broken up by the AL plate, at high impact velocity (5km/s or 6km/s) it is broken up into big fragments which has low dispersing velocity. When the target is AL mesh, the result is totally different. The projectile is broken up at all the test velocities (3km/s, 4km/s, 5km/s, 6km/s); the impact fragments are smaller and have higher dispersing velocity.

According to the source, the impact fragments are separated into projectile fragments and target fragments. To be more specific, projectile fragments and target fragments are separated into uprange fragments and downrange fragments. Because of 99% of the projectile fragments are downrange fragments, the mass of this part fragments only show a slight difference at different impact velocity, however the mass difference of uprange fragments from the projectile is obvious. When the target is AL mesh, the $m_{p\text{-}up}$ increases as the impact velocity increases, when the target is AL plate, the $m_{p\text{-}up}$ decreases as the impact velocity increases, as shown in Fig. 5.

The fragment from the target can share some kinetic energy from the projectile to decrease the damage caused by the projectile fragment, on the other side, the target fragment is also a threat to a space craft. The $m_{t\text{-}up}$ of AL plate is much heavier than that of AL mesh with the same area density, when the impact velocity is 3km/s. The $m_{t\text{-}up}$ of the AL mesh seems to have no relationship with the impact velocity and the projectile diameter, as shown in Fig. 6. The $m_{t\text{-}down}$ of AL plate is less than that of AL mesh with the same area density at all simulated impact velocities. The larger the projectile diameter, the lighter the $m_{t\text{-}down}$ of AL meshes.

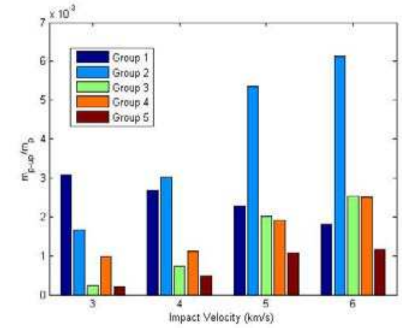


Fig 5. Mass of Uprange Fragments from Projectile

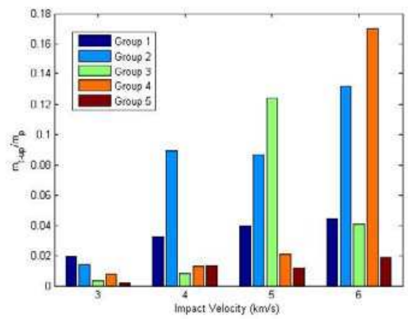


Fig 6. Mass of Uprange Fragments from Target

3.2 Fragments Motion

In the process of impact, complicated shock wave propagation exists in the fragments. If the intensity of shock wave is large enough it could lead to further disruption of the fragments. The shock wave attenuated rapidly when traveling in metal, all the fragments should achieve uniform motion in several microseconds after the impact. In the analysis below, all the velocity of the fragments are measured at 6 microseconds after the impact.

The shield capability can be evaluated in two ways, i.e. the capability of deceleration the projectile and the capability of dispersing the fragments, which related to the axial velocity (velocity along –Z direction) and the tangential velocity (velocity at XY plane). The average velocity data of the fragments from each part is shown in table x, all the velocities are normalized by dividing various measured velocity by the impact velocity and be treated as scalar.

The normalized average axial velocities of the projectile fragments as a function of the impact velocity are shown in Fig. 7. Given a combination of projectile and target, the normalized average axial velocity increases slightly while the impact velocity increases, no matter the target is AL mesh or AL plate. The shape of the curve is consistent with NASA's experiments[8] as shown in fig 8, the sketch at the right bottom of the figure is the basic shape of the debris cloud produced by impacting AL plate with sphere projectile, in which point 2 is the cg of fragments, the axial velocity of point 2 is measured by series of X-ray photographs. The relationship between normalized axial velocity and impact velocity is shown as curve 2, which shares the same shape with that in Fig 7. The difference between group 1 and group 2 show that with the same area density AL mesh has a better performance at deceleration projectile than AL plate. The curves of group 3, group 4 and group 5 show that the deceleration performance of the AL mesh becomes worse as the impact velocity increase.

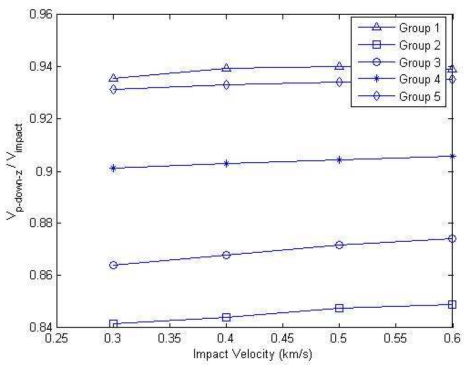


Fig 7. Axial velocity of downrange fragments from projectile vs impact velocity

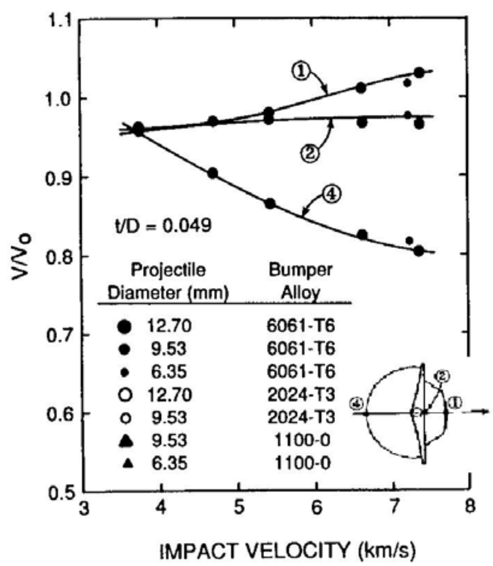


Fig 8. Debris cloud axial velocity vs impact velocity[8]

The average tangential velocities of the projectile fragments as a function of the impact velocity are shown in Fig. 9. The normalized average tangential velocity increase is occurred when the impact velocity increase. The AL mesh still has a better performance at dispersing the projectile fragments than AL plate with the same area density. The dispersing performance of the AL mesh becomes worse as the diameter of the projectile increase.

3.3 The Impact Load Formed by the Fragments

Impact load is the accumulation of impulse in a short time. The distribution of the impact load on an object has a direct relation with the damage level of the object. The distribution pattern of the impact load provide a way to evaluated the threat level of the fragment produced by impacting AL mesh or AL plate. Usually a witness plate is placed to get the distribution of impact load, a virtual witness plate is needed. It is assumed there is a witness plate 4 cm behind the target (AL mesh or AL plate). Then calculate all the particles that pass through the witness plate within 20us after the impact. Take group 1 and group 2 as example to study the difference between mesh and plate, as shown in Fig. 10. In Fig. 10, the value of the maximum point of the impact load of group 1 (target is AL plate) is higher than that of group 2 (target is AL mesh). The local peaks of impact load are centralized in group 1 and sporadic in group 2.

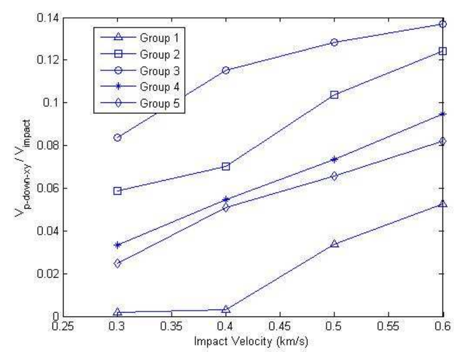
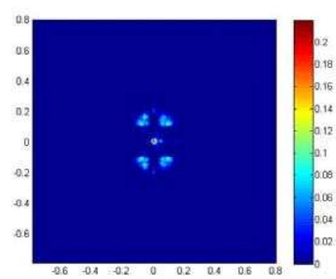
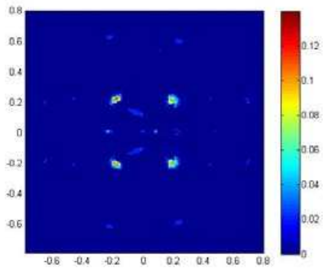


Fig 9. tangential velocity of downrange fragments from projectile vs impact velocity



a. group 1, 5km/s



b. group 2, 5km/s

Fig 10 Impact Load Distriubtion

4 CONCLUSIONS

Numerical simulation of aluminum projectile impacting on AL mesh has been carried out in this paper. After analyzing on the mass of fragments, the kinetic character of fragments and the impact load formed by the fragments, it is concluded that:

1. When impacting AL mesh at low velocity (3~4km/s), the projectile fragments are consist of several big fragments and many small fragments, as the impact velocity increases, the fragments becomes smaller and more even.
2. The AL mesh has a better performance at disrupting projectile and dispersing fragments than AL plate with the same area density.
3. More fragments emit from the AL mesh when impacting by projectile with bigger diameter.
4. AL mesh has worse performance at deceleration and dispersing when impacting by projectile with bigger diameter.
5. The value of maximum impact load distribution is higher and the local peaks are centralized when the target is AL plate, the value of maximum point is lower and local peaks are sporadic when the target is AL mesh.

Single AL mesh has a good ability of breaking up and dispersing projectile. However, the fragments prouced by impacting AL mesh exist localized energy concentration, further disruption and dispersing is needed to minimize the threat level of the fragments.

REFERENCES

1. Christiansen E.L, Advanced meteoroid and debris shielding concepts. AIAA/NASA/DOD Orbital Debris Conference, AIAA 90-136, 1990
2. Horz F, Cintala M.J, See T.H, Bernhard R.P, Cardenas F, etc. Comparisons of continuous and discontinuous bumpers: Dimensionally scaled impact experiments into single wire meshes, NASA TM 104749, 1992
3. Horz F, Cintala M.J, See T.H, Bernhard R.P, etc. Impact experiments into multiple-mesh targets: Concept development of a light-weight collisional bumper, NASA 104749,1993
4. Christiansen E.L. and Kerr J.K, Mesh double-bumper shield: A low weight alternative for spacecraft meteoroid and orbital debris protection, Int. J. Impact Eng, 14, 1-4, 169-180,1993
5. LI Yi, LIU Sen, HUANG Jie. Debris Cloud Characteristics of Mono- and Multi-plates Under Hypervelocity Impact. 4th Symposium of Space Debris, China, 2007
6. Liu Sen, Li Yi, Huang Jie. Hypervelocity Impact Test Results of Whipple Shield for the Validation of Numerical Simulation. Journal of Astronautics, v26, n4, July, 2005.
7. Li Yi, Liu Sen. Numerical Simulation for Hypervelocity Impact of the Spacecraft's Aluminum Panel. Manned Spaceflight. 2004.
8. Piekutowski A.J. Formation and Description of Debris Clouds Produced by Hypervelocity Impact, NASA Contractor Report 4707, 1996