Hypervelocity impact of tungsten cubes on spaced armour

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Abstract: The paper summarizes the experimental observations and simulation studies of damage potential of tungsten alloy cubes on relatively thin mild steel spaced armour target plates in the velocity regime 1300 – 4000 ms$^{-1}$ using Two Stage Light Gas Gun technique. The cubes of size 9.5 mm and 12 mm having mass 15 g and 30 g respectively were made to impact normally on three target plates of size 300 mm × 300 mm of thickness 4, 4 and 10 mm at 100 mm distance apart. Flash radiography has been used to image the projectile-target interaction in the nitrogen environment at 300 mbar vacuum at room temperature. The results reveal clear perforation by 9.5 mm cube in all the three target plates up to impact velocity of about 2000 m/s. While 12 mm cube can perforate the spaced armour up to impact velocity of 4000 m/s. This shows that 9.5 mm tungsten alloy cube is not effective beyond 2000 m/s while 12 mm tungsten alloy cube can defeat the spaced armour up to 4000 m/s. The simulation studies have been carried out using Autodyn 3D nonlinear code using Lagrange solver at velocities 1200 – 4000 m/s. The simulation results are in good agreement with the experimental findings.

1. Introduction

The penetration capabilities of fragments cannot be estimated using available empirical relationships which are not valid for hypervelocity impacts. The basic theories have focused principally to predict the mean fragment size through energy and momentum balance principles [1-4] and on statistical issues of mean fragment size distributions [5-8]. However, there are number of unresolved issues within the development of statistical energy-balance theories of fragmentation which led to a pressing need for hypervelocity experimental data in order to optimize the fragment parameters to cause the desired damage to the target.

The implementation and validation of these basic theories in numerical wave propagation codes is needed to investigate dynamic fragmentation in large scale complex problems. Dynamic failure and fragmentation data of solids is required to characterize and understand the material behavior under intense stress-wave loading conditions. Although the static data exist for these materials, but this does not suffice to in-depth theoretical understanding of solids under highly dynamic regime.

The present study addresses the threshold breakup speed and damage potential of the tungsten alloy cube fragments of size 9.5 mm and 12 mm made to impact normally upon relatively thin plates (Plate Thickness/Fragment Diameter, T/d < 1) in a vacuum 300 mbar with plate spacings greater than several fragment diameters. The experiments in the velocity regime 1300 - 4000 ms$^{-1}$ have been carried out using Two Stage Light Gas Gun facility at room temperature. At lower impact velocity, the fragments perforate thin plates without much deformation or mass loss. Above threshold impact speed, the projectile starts to disintegrate into smaller fragments. As the impact speed increases, the high speed larger particles from 12 mm cube fragment debris cloud perforated second and third target plates but relatively smaller debris cloud particles from 9.5 mm cube fragment could not perforate all the three plates. The axis of the cloud is aligned with the line of fire. Dispersion of fragment debris particles also increases with increase in impact speed.

The simulation studies have been carried out using Autodyn 3D nonlinear code using Lagrange solver at velocities 1200 – 4000 m/s.
2. **Experimental Details**

The experiments were conducted using Two Stage Light Gas Gun Facility at TBRL, Chandigarh using Polycarbonate Sabots, custom designed in-house to impact the target plate edge on. The Target assembly is rigidly fixed within the Chamber-3 (see Fig 1) along the axis line. The projectile assembly (as shown in Fig 2) is launched by 29 mm and 40 mm calibers into the chambers, which are first evacuated to 30mBar and then filled with nitrogen gas to 300 mBar.

The tungsten alloy cubes mounted in polycarbonate sabots were launched at impact velocities from about 1200 to 4000 m/s and made to impact the target array edge-on. The target array consists of three plates made up of mild steel of size 300 mm × 300 mm of thickness 4, 4 and 10 mm at 100 mm distances apart. Polycarbonate sabots were separated through forces produced by inert nitrogen gas atmosphere filled at 300 mbar in chamber 2. Sabot fragments were arrested upstream by sabot catcher plates and did not reach the target plates.

Laser beam sensors and Aluminium foil sensors were deployed along the flight path in Chamber-1 and 3 to record the velocity of the impactor (shown in figure 3). The cube impacting edge-on and fragment – plate particle clouds were radiographed at two stations by two 150 keV x-ray tubes (Make: Scandiflash) placed orthogonal to the line of fire as shown schematically in figure 4. The delay times were calculated from the predicted impact velocity and the x-ray tubes were triggered independently by orthogonally placed laser barriers during flight and by PCB sensors on the target plates. The impact velocity was predicted by optimizing various ballistic parameters through CESAR simulation software. PCB sensors are affixed on the target plates to trigger orthogonal flash X-rays as well as to measure arrival time of impactor.
3. Results and Discussion

An extensive experimental and numerical study was carried out to analyze the penetration effectiveness of 9.5mm and 12mm cube fragments. Experiments were conducted using two-stage light gas gun. About 8 to 10 experiments were conducted for each cube size in the velocity range from about 1300 – 4000 m/s against identical spaced armour plate assemblies. Numerical simulations were carried out using explicit finite element code ANSYS AUTODYN to verify the observations made from experimental results. Since the problem involved large deformations and fragmentation of the projectile as well as target, smooth particle hydrodynamics (SPH) solver has been used in the analysis. The target and projectile material was modeled using Steel 1006 and Tung. Alloy properties available in AUTODYN material library. The summary of material properties is given in Table1.

Figure 5(a) and 5(b) shows the experimental and simulation results for impact of 9.5mm cube. The radiograph and simulation shows the cube impacting edge-on and dispersions of the fractured cubes behind the second target plate at impact velocity of about 4000 m/s. It has been observed that 9.5 mm cube is effective in the velocity window 1300-2000 ms⁻¹ only. Above this threshold impact speed, the projectile starts to disintegrate into smaller particles. With the increasing impact velocity, the fragment breakup become more severe; the sizes of debris particles decrease and the number of particles increase. It can also be seen that the dispersion of fragment debris also increases with increasing impact velocity. The perforating debris particles loose momentum and may perforate or produce cratering effect on the next plate. As the impact velocity increases, the density of fragments increases. While 12 mm cube can perforate all the three target plates even up to 4000 m/s. Figure 6 shows that as the cube size is increased, the size of fragment debris particles and dispersion is relatively lower that 9.5 mm cube fragment. The larger fragment particles possess sufficient momentum to perforate subsequent plates.

Impact pressure and relief wave mechanisms are predominant in the generation of fragment and plate particle population clouds. Impact pressure at the interface can be relieved laterally as well as in the direction normal to the interface. For small T/d (plate thickness to fragment diameter) ratio, radial velocities in the plate are relatively small but as the T/d ratio increases, radial components become greater [9-10]. This was revealed by flash radiographs as shown in figures 5 and 6. Thus the impact velocity which governs stress intensity and normalized plate thickness T/d which governs the relative magnitude of radial stress are the predominant factors in fragment and plate fragmentation.

Table1: Material properties used for numerical simulation.

| Projectile – Tung. Alloy | Target – Steel 1006 |
|--------------------------|----------------------|
| **Equation of State - Shock** | **Equation of State - Shock** |
| Reference density | 17.0 g/cc | Reference density | 7.896 g/cc |
| Gruneisen coefficient | 1.54 | Gruneisen coefficient | 2.17 |
| Parameter C1 | 4.029e+003 m/s | Parameter C1 | 4.569e+003 m/s |
| Parameter S1 | 1.237 | Parameter S1 | 1.49 |
| Specific Heat | 134.000015 J/Kg K | Specific Heat | 451.999969 J/Kg K |
| **Strength Model – Johnson Cook** | **Strength Model – Johnson Cook** |
| Shear Modulus | 1.60e+008 kPa | Shear Modulus | 8.180001e+007 |
| Yield Stress | 1.506e+006 kPa | Yield Stress | 3.500000e+005 |
| Hardening Constant | 1.77e+005 kPa | Hardening Constant | 2.750000e+005 |
| Hardening Exponent | 0.12 | Hardening Exponent | 0.36 |
| Strain Rate Constant | 0.016 | Strain Rate Constant | 0.022 |
| Thermal Softening Exponent | 1.00 | Thermal Softening Exponent | 1.00 |
| Melting Temperature | 1.723e+003K | Melting Temperature | 1.811e+003K |
4. Conclusions
It is concluded that small size 9.5 mm tungsten alloy cube is not effective beyond 2000 m/s while 12 mm tungsten alloy cube can defeat the spaced armour upto 4000 m/s. The impact velocity and normalized plate thickness T/d are the predominant factors responsible for impactor and plate fragmentation. The simulation results carried out using Autodyn 3D explicit finite element code using SPH solver at velocities 1200 – 4000 m/s support the experimental findings.

5. Acknowledgements: The authors are thankful to Mr Sohan Lal, Tech ‘A’ and Mr GN Jha Tech ‘A’ for their assistance in conducting experimental trials.

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