Hypervelocity impact of aluminium sphere against aluminium plate : experiment and LS-DYNA correlation

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Abstract

High velocity impact of 3 mm diameter aluminium sphere against thin aluminium target plate has been performed at impact velocity of about 4000 m/s with the two stage light gas gun HERMES at Thiot Ingenierie laboratory. Impacts at normal incidence and with a 32° angle generate debris clouds that were collected by an aluminium witness plate. The visualization of the debris clouds generated after the impact has been realized by using an ultra high speed framing camera. LSDYNA 3D Smooth Particle Hydrodynamics and 2D&3D Multi-Material ALE solvers (MMALE) were used to reproduce debris clouds generation and expansion in the two angle configuration. Agreement between simulations and experimental frames are discussed.

Keywords: Aluminium, Hypervelocity impact, High speed Framing Camera, Two-stage light gas gun, SPH, MMALE

INTRODUCTION

Hypervelocity impact on spacecraft structures is a continuous challenge for engineers to design efficient and light protection devices for more than 50 years [1-4]. In this way, numerous experimental tests have been intensively performed to reproduce impacts in well known conditions (nature of materials, dimensions, velocity …) by typically using two-stage light gas gun shots. Those data ensure a continuous development of hydrocodes in this field but it always needs to find the right configuration between solver, grid size mesh optimization and equation of state, strength, fracture and numerical erosion with their well-calibrated parameters.

This paper presents the comparison between numerical results obtained using two types of solver, Eulerian and SPH. Debris clouds characteristic velocity and shapes comparison with frames recorded by an electronic high speed framing camera during shots are proposed. This study firstly evaluates the capacity of the LSDYNA code to reproduce the whole shape of the debris cloud fragment and secondly analyzes from a restricted choice of parameters what is the right solver that best reproduces high speed impact events. In this study, comparisons concern results from a 3 mm diameter sphere aluminium that impacts at 4 km/s a 2 mm thick aluminium plate with a normal incidence and with a 32° tilted impact configuration.

EXPERIMENTAL PROCEDURE

Hypervelocity impact tests were performed with the HERMES two-stage light gas gun (Figure 1) at Thiot Ingenierie Laboratory [5]. This gun differs from others standard two-stage light gas guns because of a first stage gas gun instead of a conventional gunpowder. This “whole gas version” avoids the use of powder and so all the problems due to pyrotechnic safety.

The gas breech is a wrap-around design which can accept Helium or Nitrogen. The launch tube caliber is 12 mm and it can be precompressed with Helium or Hydrogen. Maximum pressure in the gas breech is 400 bar and common pressure in the pump tube ranges from 5 to 20 bar. In this configuration, a maximum velocity of 5500 m/s has been achieved with a projectile mass of 2.0 g.

For the experiments depicted in this paper, the projectile was a two-part sabot with a 3.0 mm ball of aluminium. Vacuum level in the launch tube and in the impact chamber was 300 mbar in order to allow the separation of the sabot.

Triggering of the metrology was done by optical barriers and by self-shorting contacts. Impact velocity of the aluminium ball was performed by calculation of the chronometry between all these time informations and also by the time informations given by the camera.

The camera used in this study was an electronic ultra high speed framing camera SIM8 (Figure 2) designed and built by Specialised Imaging Limited [6]. This camera is based on ultra high resolution intensifiers and gives 1360(H) x 1024(V) 12 bit images. It is computer controlled via standard ethernet link and is able to give a 5 ns interframe time with a 5 ns exposure time. This Multi-Channel Framing Camera may be programmed to take an 8-frame sequence with initial delay of several microseconds, this value being tuned shot by shot with respect to the trigger.

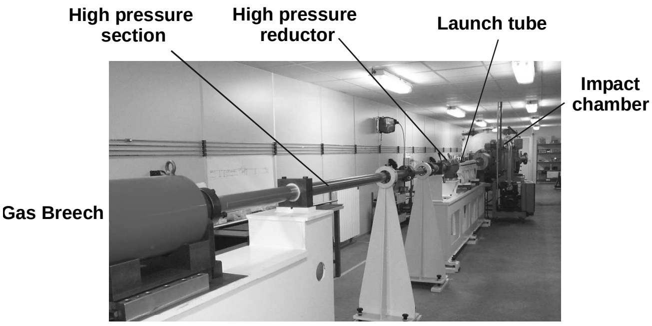

Figure 1 : Picture of HERMES two stage light gas gun

Figure 2 : SIM8 high speed framing camera

Experimental parameters of the two experiments performed in this study are presented on Table 1. Projectile is an aluminum sphere 3.0 mm in diameter and witness plate is located 30 mm behind the target. Projectile material is Al1100, target and witness Al2024. For the second experiment, target has been tilted with an angle of 32°.

The 8 frames obtained during experiments #HE0034 and #HE0035 are presented on Figure 3 and Figure 4. Interval time between two frames is 2 µs and exposure time is 20 ns for each frame.

These frames show the evolution of the debris cloud with a very fine definition for the details. The 'Driving Badminton' shape observed on the first pictures is characteristic of this range of high velocity impact and experimental configuration.

In experiment #HE0034, trigger problem had led to a delay time for the first frame, so the aluminum projectile was not observed. This problem has been solved for the following experiment #HE0035. The two first frames obtained during this experiment (Figure 4) show the aluminum projectile before the impact on the target.

The high quality of frames obtained during these two experiments gives a lot of detail on the shape of the debris cloud. For instance, the evolution of the shape of the debris cloud observed on Figure 4 indicates that the rear part of this cloud impact the front face of the target which gives a luminous phenomenon (frame #3 and #4).

A lot of quantitative information could be derived from these records and from recovered target, and could be compared to others results: target hole diameter, debris cloud diameter, debris cloud velocity,

TABLE 1 : Parameters of the two tests performed on aluminium plate

Shot ID	Projectile diameter (mm)	Target thickness (mm)	Witness plate Thickness (mm)	Distance target-witness (mm)	Incidence	Impact velocity (m/s)
HE0034	3.0	2.0	1.0	30	Normal	4119 ± 70
HE0035	3.0	2.0	1.0	30	32°	4050 ± 70

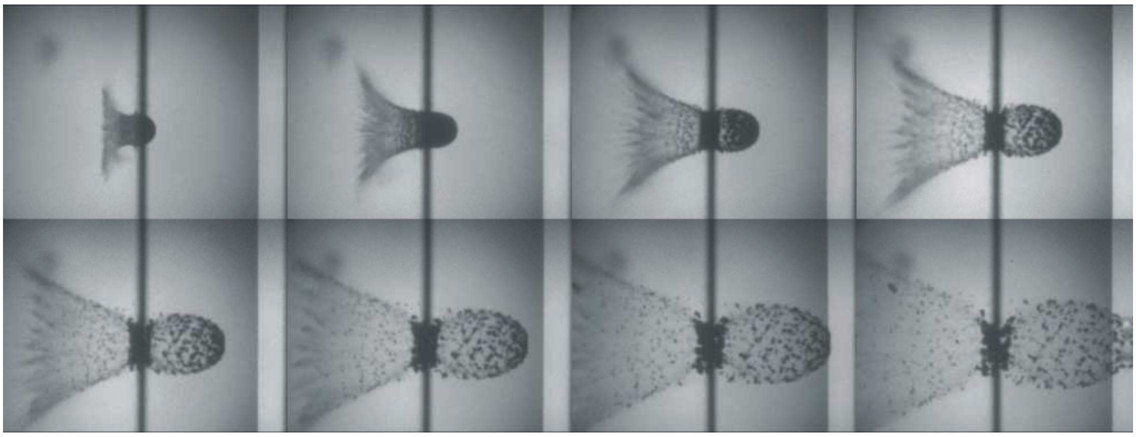

Figure 3: Observation of the evolution of the debris cloud during shot #HE0034 : 3.0 mm diameter Al1100 projectile impact 2.0 mm Al2024 target at a velocity of 4119 m/s. Interframe time is 2 µs and exposure time was 20 ns for each frame.

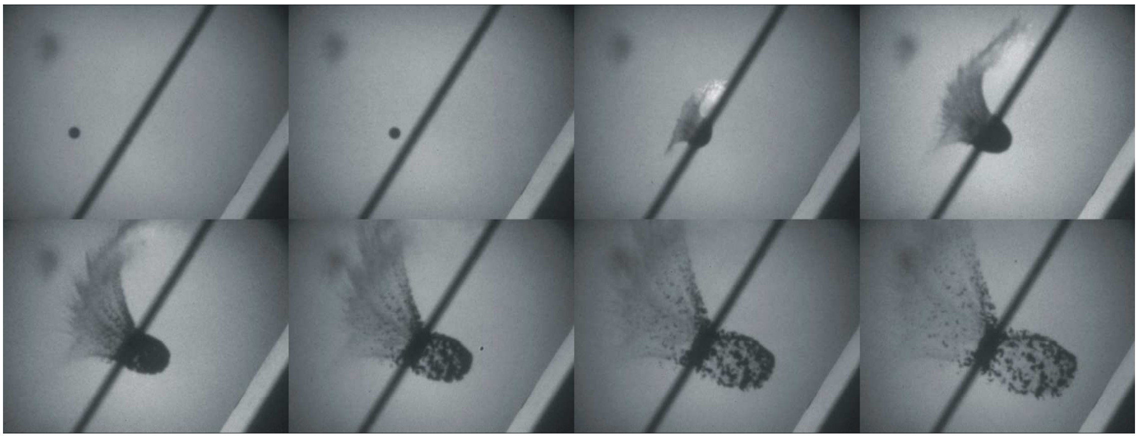

Figure 4: Observation of the evolution of the debris cloud during shot #HE0035 : 3.0 mm diameter Al1100 projectile impact 2.0 mm Al2024 target at a velocity of 4050 m/s. Interframe time is 2 µs and exposure time was 20 ns for each frame.

SIMULATIONS

Simulations have been done using the non-linear explicit code LS-DYNA. Experimental results are compared to numerical results given by 3D-Euler multi-material and 3D-SPH solvers with plane symmetry. Euler multimaterial solver has been widely used for impact phenomena at medium velocity to hypervelocity range because pressure, stress and temperature levels make material reacts more like fluid than solid. A lot of literatures present results and comparison with experiment in military applications or in space debris clouds analysis [7]-[9].

The SPH solver was firstly introduced in the late 70’s for astrophysics. It is a Lagrangian method with a variable nodal connectivity. It is gridless and thus can handle severe distortions without grid tangling and so does not need the use of unphysical erosion algorithms. This technique is then well adapted for hypervelocity phenomena simulations [10]-[12]. A Mie-Gruneisen equation of state and a standard strength model is selected for aluminum. Parameters are indicated in Table 2.

The first calculation has been performed with a multi-material eulerian formulation. The mesh of the space required for this configuration is presented on Figure 5. The plate lateral dimension has been reduced to an acceptable number of elements.

Results of calculation are illustrated on Figure 6 and Figure 7. Comparison with experimental frames of Figure 3 shows that Eulerian formulation allows to reproduce the whole behaviour of the fragments behind the plate. On the contrary, the rear plumes created at the back of the plate is not obtained by simulation.

Table 2 : Parameters of EOS and strength model for aluminum

Equation	Parameters	
Mie Gruneisen	Initial density ρ_0	2.7 g/cm^3
	Bulk wave velocity C_0	5328 m/s
	Shock wave velocity parameter S	1.338
	Grüneisen coefficient Γ_0	2.0
Mat elastic plastic hydro (in LS-DYNA)	Shear modulus G_0	28.6 GPa
	Elastic limit σ_y	260 MPa

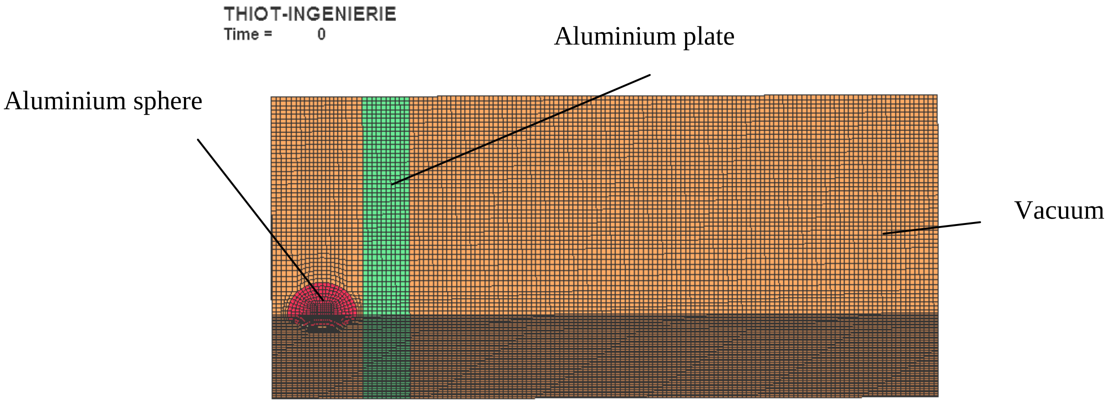

Figure 5 : Eulerian mesh for the simulation of test #HE0034

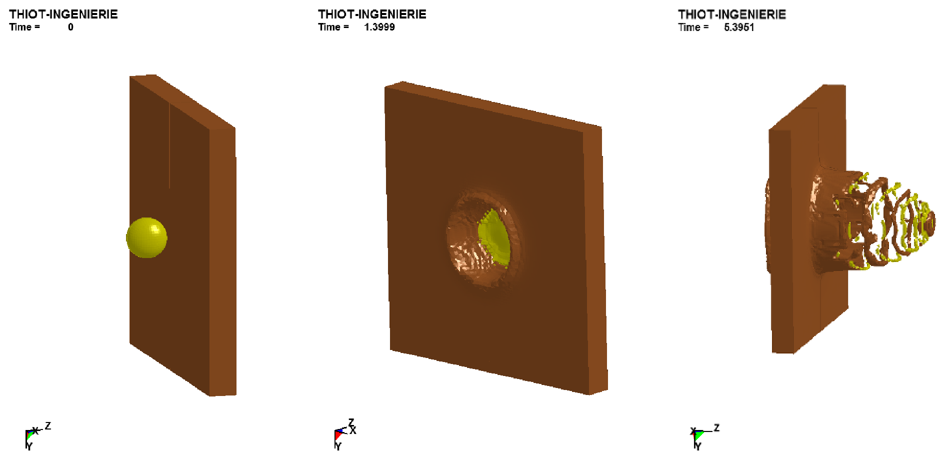

Figure 6 : Impact visualisation (two faces of the simplified plate) for simulation of test #HE0034

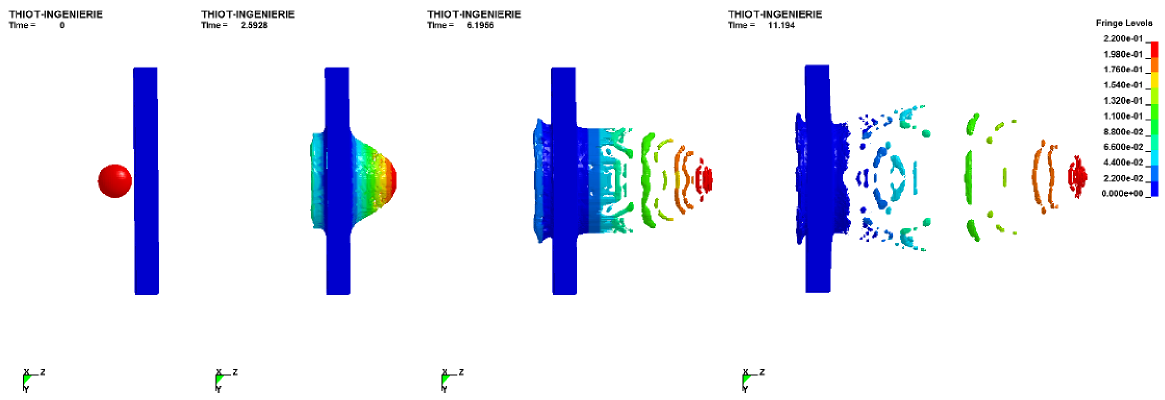

Figure 7 : Fluid visualisation of the impact (scale velocity locked between 0 en 2200 m/s) for simulation of test #HE0034

The second calculation of this configuration has been performed using SPH modeling with the initial conditions indicated on Figure 8. A 100 mm by 100 mm plate has been considered for the aluminum target with a 20 mm by 20 mm SPH zone for the impact. The transition between SPH elements and lagrangian finite elements is realized with a tied contact. The new hybrid SPH / solid element is used to obtain a better transmission of the shock wave at this interface.

Figure 9 shows comparison between HE0034 experiment and simulation. From a qualitative point of view, the whole shape of the debris cloud is reproduced by the simulation. The rear plumes generated by the impact are very similar but projection angle is higher in the simulation. Moreover the axial velocity of the cloud is 10 % higher than the experiment.

Figure 10 shows the shock wave propagation in the target plate. There is a correct transition between SPH zone and solid zone but it appears that the shape of the compression waves follows the quadrangular shape of the mesh. This is an artifact of the numerical schema.

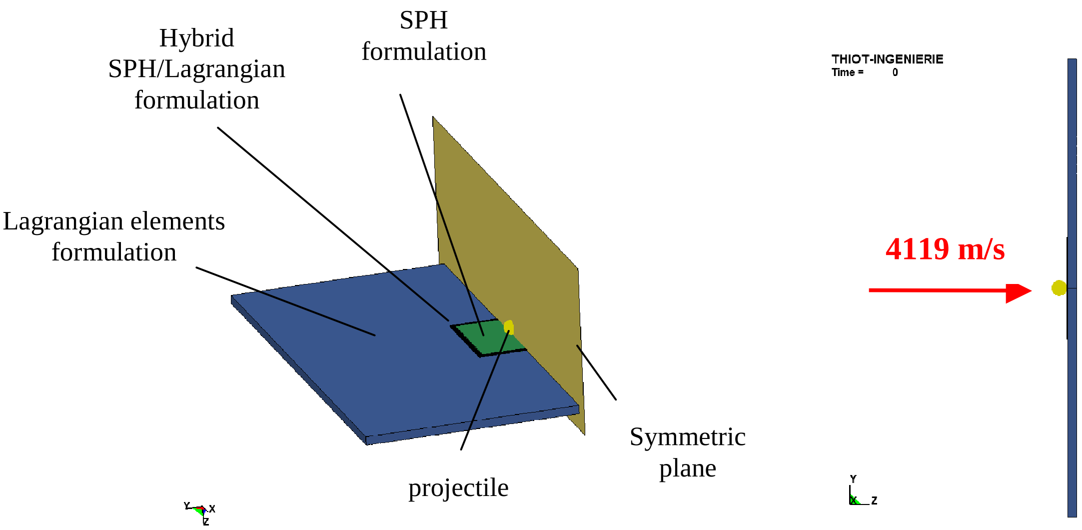

Figure 8 : Initial condition and configuration for the second calculation (SPH schema) test #HE0034

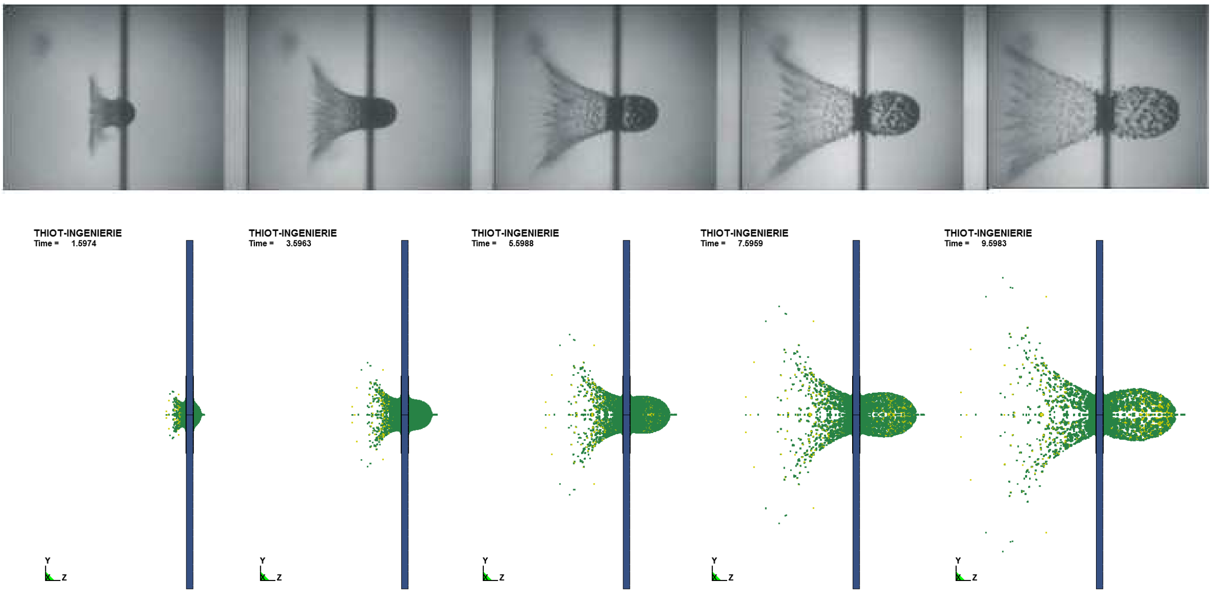

Figure 9 : Correlation between experiment and calculation (one frame every 2 µs) test #HE0034

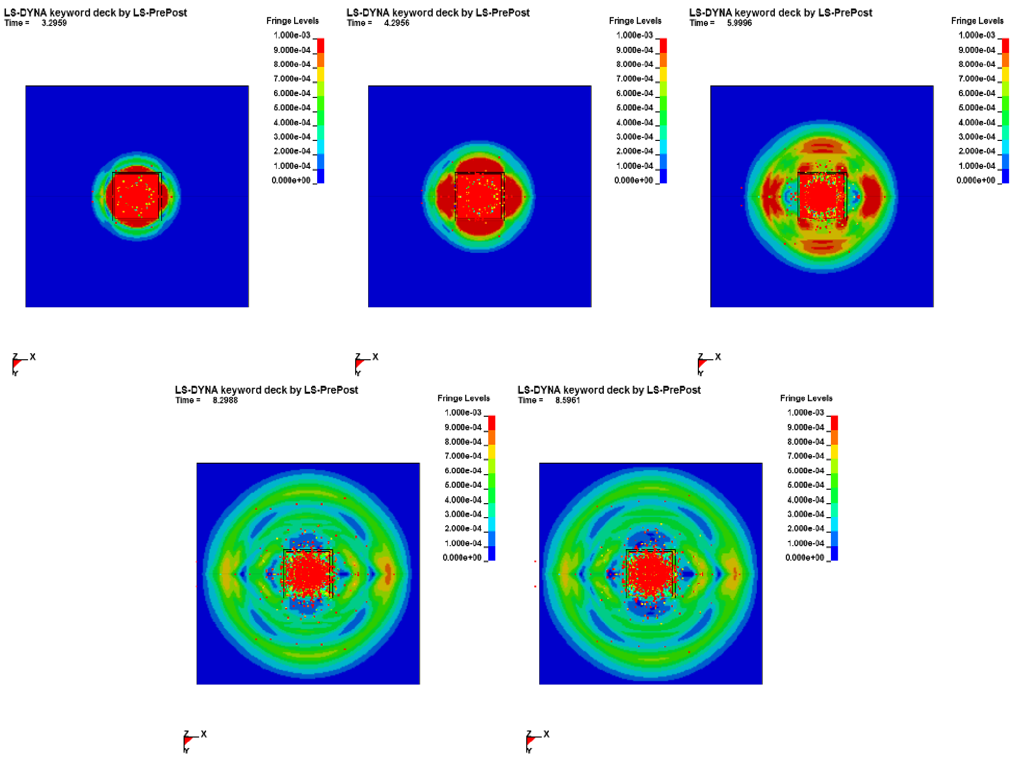

Figure 10 : Shock wave propagation in the target plate (Von Mises stress between 0 and 100 MPa) test #HE0034

The simulation of test #HE0035 has been performed using SPH modeling with the initial conditions indicated on Figure 11. As for the previous simulation, the target plate is divided in a central zone with SPH elements and an outer area considered as solid.

Figure 12 shows comparison between #HE0035 experiment and simulation. From a qualitative point of view, the whole shape of the debris cloud is reproduced by the simulation. The rear plumes generated by the impact are very similar and especially in terms of ejection angles (top and bottom) and in terms of fragments density. Fastest small fragments splash back followed by heavier fragments at lower speed. The characteristic shape generated at the rear of the target in the simulation is approximately the same than that given by the experiment. The main axis of the debris cloud (direction of the fastest fragments from the impact point) seems to be well reproduced. The rear plumes ejection angle is not reproduced after 6 µs.

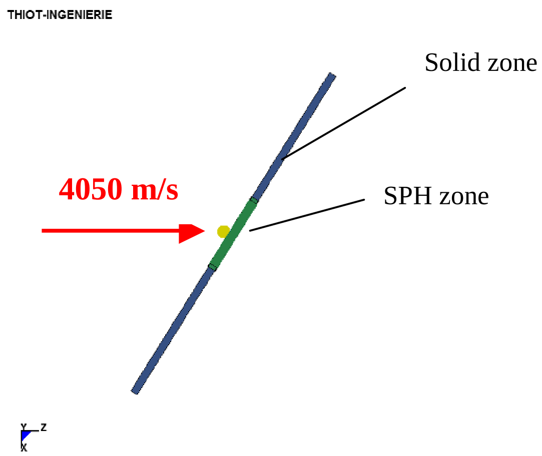

Figure 11 : Configuration of the simulation for test HE0035**.**

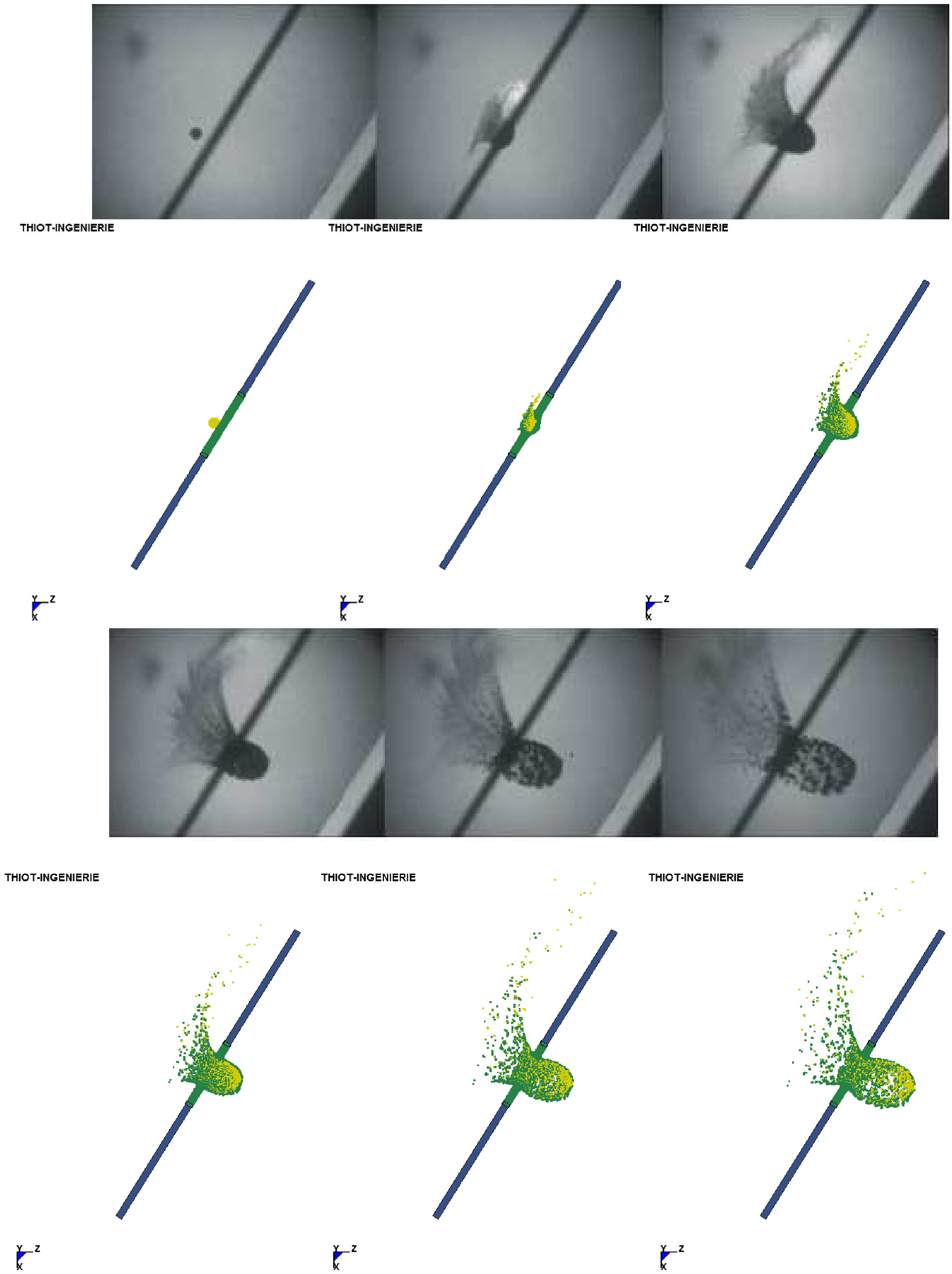

Figure 12 : Correlation between experiment and calculation (one frame every 2 µs) test #HE0035

RESULTS AND DISCUSSION

All the simulations presented in this paper give higher expansion velocities and higher axial velocities of the debris cloud than in experiments. For the tilted impact, the angle between the shot line and the main axis calculated by simulation is 14.3° which is smaller than the value of 20° measured in the experiment. However, 3D-SPH particles results are closest to the experiments for the tilted impact HE0035.

These results show again the potentiality of SPH method to reproduce the debris cloud observe during hypervelocity impact. Mie Grüneisen equation of state and simple strength models give interesting results but a more sophisticated model taking into account multiphase EOS, thermoplastic behaviour and fragmentation is necessary to improve the correlations.

CONCLUSIONS

Numerical results obtained with LS-DYNA are consistent with high velocity impact of aluminium sphere against aluminium target performed in our laboratory. These results first validate the experimental facilities of our lab (two stage light gas gun and high speed framing camera) at this impact velocity and secondly the ability of the hydrocode to reproduce the debris clouds and expansion.The 3D SPH version of this hydrocode is the best to reproduce the shape and the velocity of the debris cloud.

Same works are under progress with LS-DYNA with some user multi-phases equation of state implementation. Higher impact velocities (6-8 km/s) with various projectile diameters and target thicknesses are planned in the future with a small bore diameter launch tube to emphasis our know-how and ensure comparison with literatures.

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