Numerical Simulation of Edge Effects of Gas Gun Experiments

M. ARRIGONI, T. Charlon
michel.arrigoni@ensieta.fr

Contributors :

M. Boustie, J.-P. Cuq-Lelandais (ENSMA)

H.-L. He, C. Hu, X. Wang (National Key Laboratory for Shock Wave, CAEP, China)

中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS

Introduction

Generation of shock waves with gas gun helps studying the dynamic behaviour of materials :

- Validation of rupture criteria

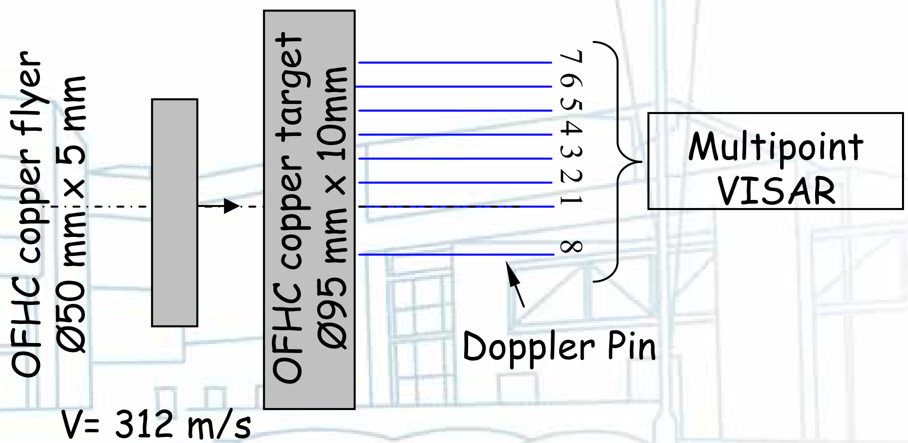
- Characterisation of materials

- Shockwave propagation (edge effects)

⇒ Use of numerical simulation (*Altair Hyperworks Radioss ®*) in this intention.

Experimental setup

- Plate impact of OFHC Copper, 5 mm thick at 312 m/s on a OFHC Copper target, 10 mm thick



Shockwave relations

Rankine-Hugoniot equations :

- Mass conservation : $\rho\,(D - u) = \rho_0 D$
- Impulse conservation : $P - P_0 = \rho_0 D\,(u - u_0)$
- Energy conservation : $E(P, \rho) - E_0 = (P + P_0)\,(1/\rho_0 - 1/\rho)/2$

Mie-Grüneisen equation of state :

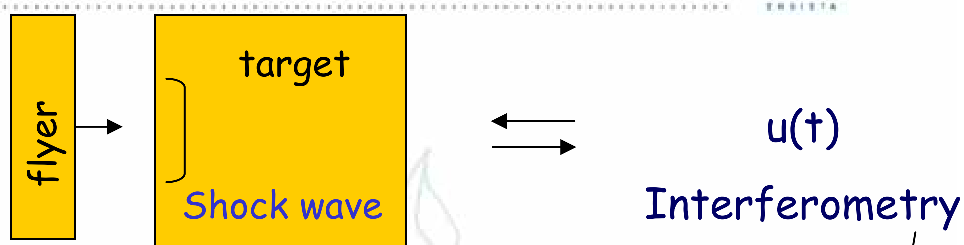
$$P(E,v) - P_0(v) = \frac{\Gamma}{v}\,(E - E_0(v))$$

Empirical relation between D and u :

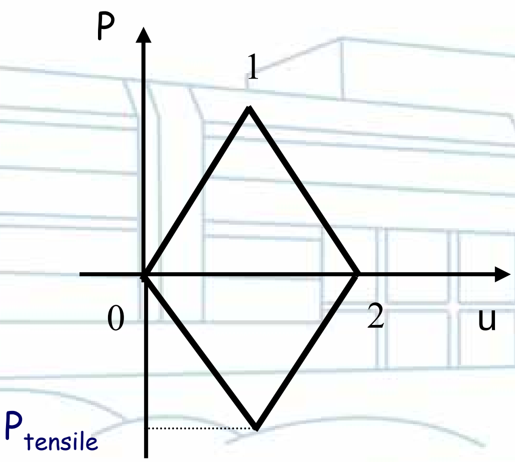
$$D = C_0 + s.(u-u_0)$$

Analytical study in 1 D

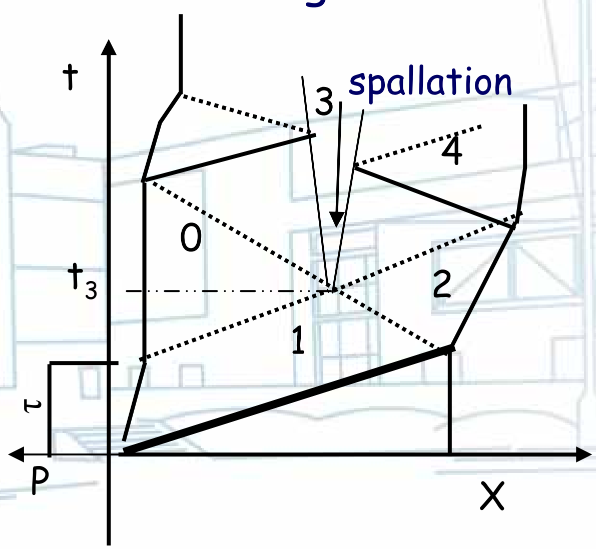
- Plate impact



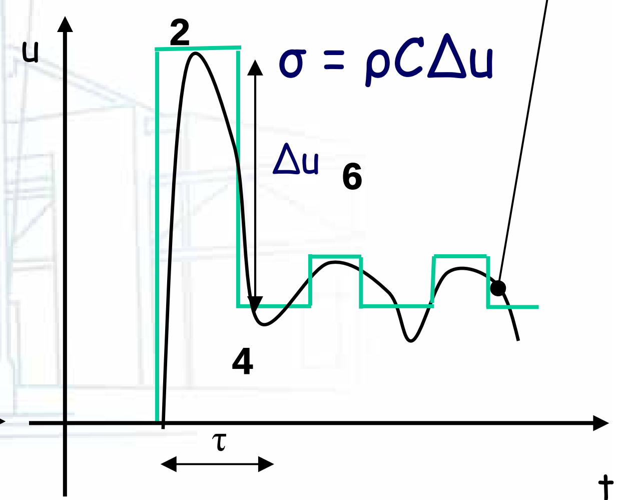
P-u diagram



x-t diagram



u-t diagram



Johnson-Cook elasto-plastic model

• Elasto plastic Johnson-Cook model :

$$\sigma_{VM} = \left(A + B(\varepsilon_p^{eq})^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_0}{T_{fusion} - T_0}\right)^m\right)$$

$$\varepsilon_p^{eq} = \sqrt{\frac{2}{3}trace(\varepsilon_p^2)}$$

A, B, C, n and *m* the Johnson Cook constants. T_0 the reference temperature (300 K) and T_{fusion} the temperature of melting.

	A (MPa)	*B (MPa)*	*C*	*n*	*m*	T_{fusion} (°K)	T_0 (°K)	(s^{-1})	(s^{-1})
OFHC Copper	90	292	0.013	0.37	1.09	1356	300	3.15	1

Tuler-Butcher damage model

- Cumulative model : rupture becomes effective when $I > K$

$$I = \int (\sigma - \sigma_r)^A \, dt$$

with $\sigma_r = \frac{1}{2} \rho \, c \, \Delta u$

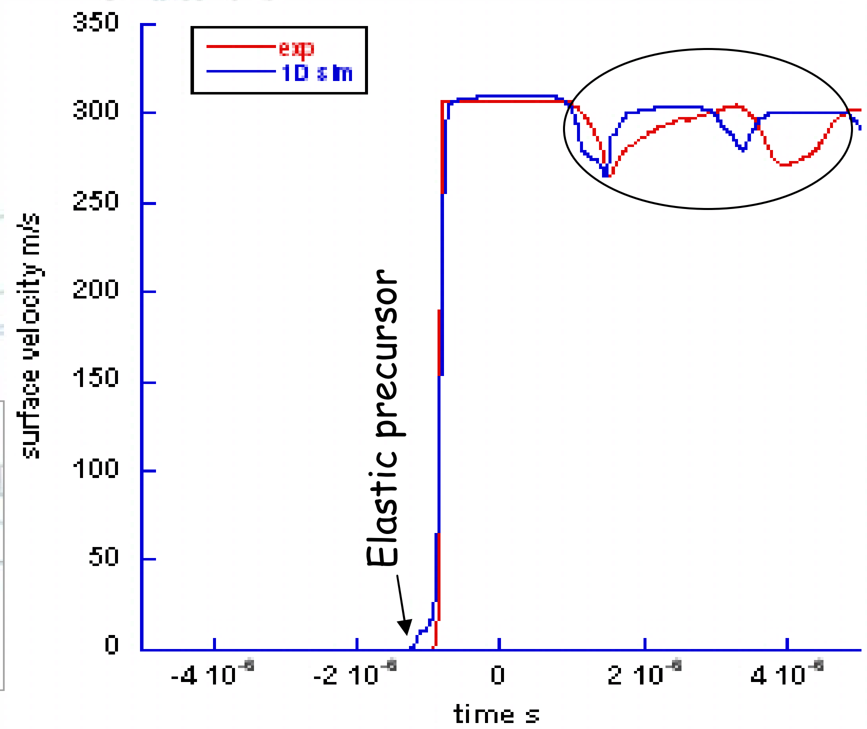
- *Not unique set of parameters (σ_r, K, A)*
- *In this study :*
    - $\sigma_r = 0.007375$ *Mbar*
    - $K = 20$
    - $A = 1.81$

Numerical simulation/experiments 1D

- Finite element analysis with 25 μm mesh size
- Satisfying up to 2 μs
- Then, edge effects => 2D !

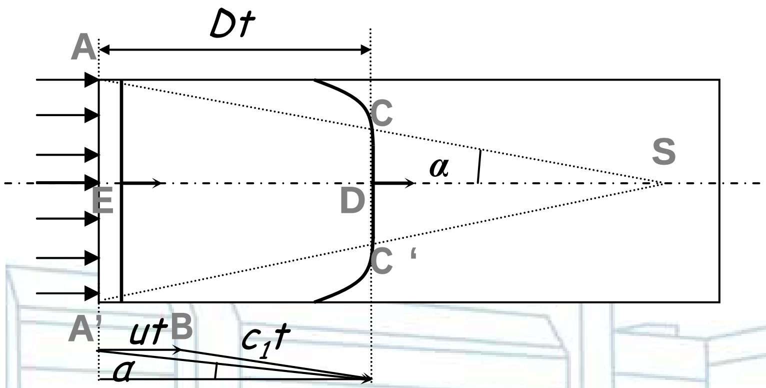
OFHC Copper :

ρ_0 (Kg/m³)	C_0 (m/s)	Γ	s	E (GPa)	ν
8960	3930	2	1.49	115	0.336



Analytical expression of edge effects

- Planar shock wave propagation after impact :



$$\tan^2\alpha = \frac{c_1^2}{D^2} - \left(1 - \frac{u_1}{D}\right)^2$$

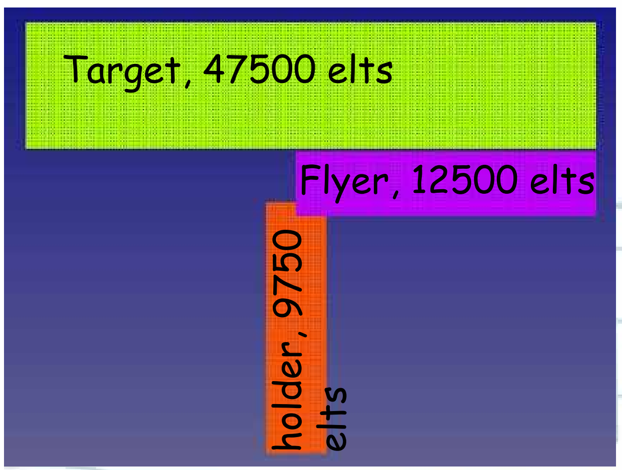
With : $c_1 = \frac{\rho_0}{\rho_1}(c_0 + 2su_1)$

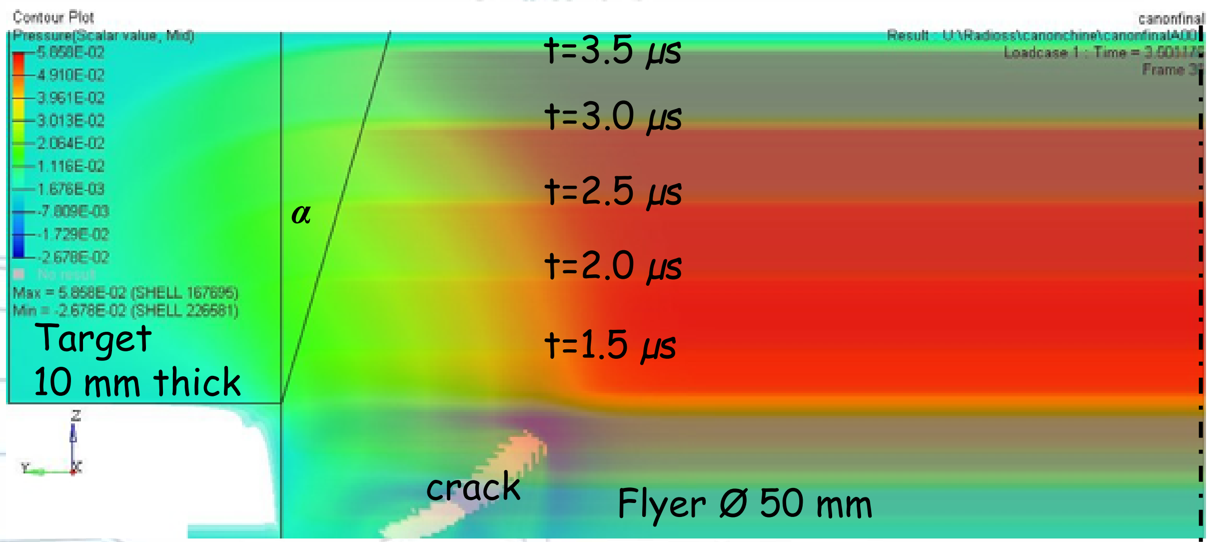
For V_{impact} = 312 m/s in OFHC Copper :

=> α = *18,1°*

2 D axisymmetric simulation

- Mesh size 100 μm.

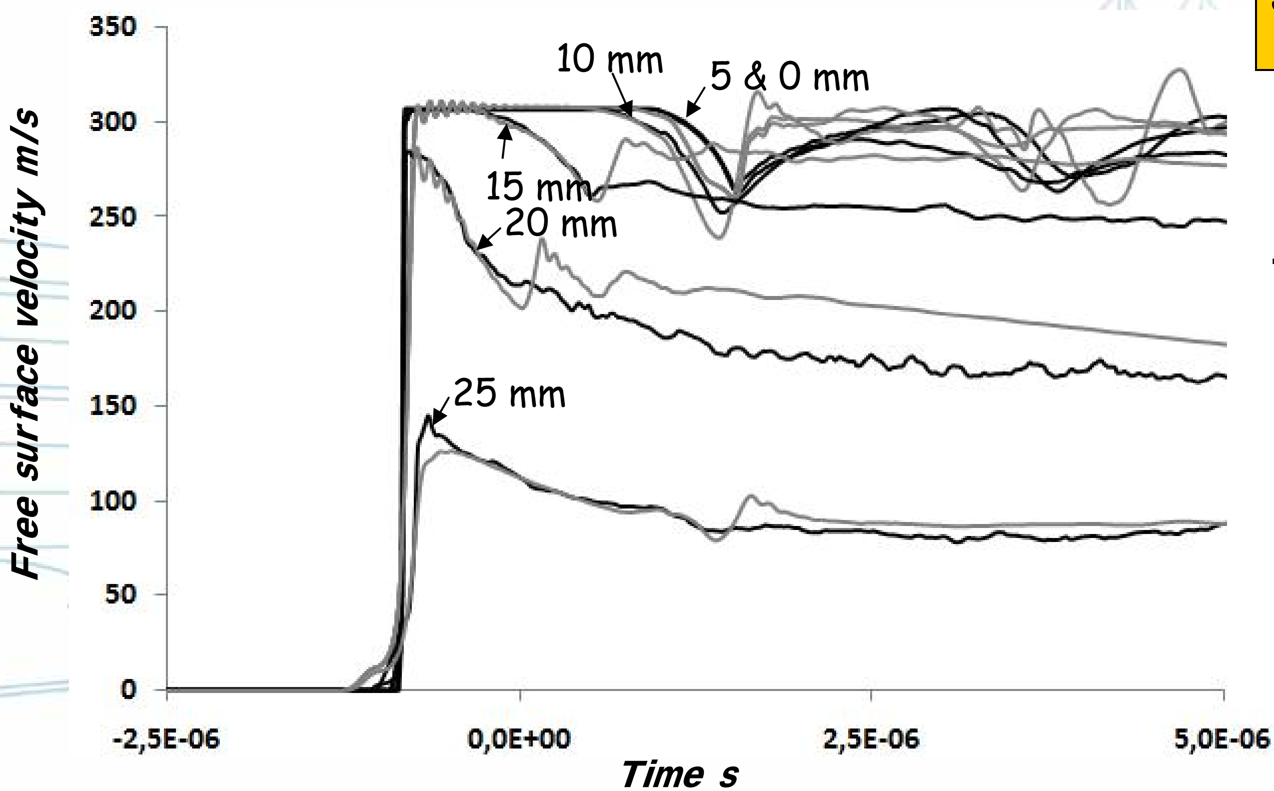


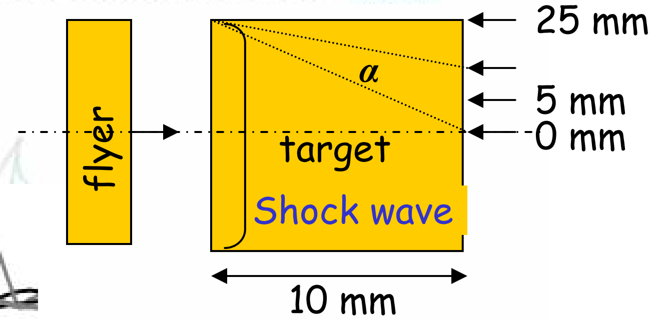


=> $\alpha = 16{,}5° \pm 1$

Free surface velocity

- Comparison with experiments

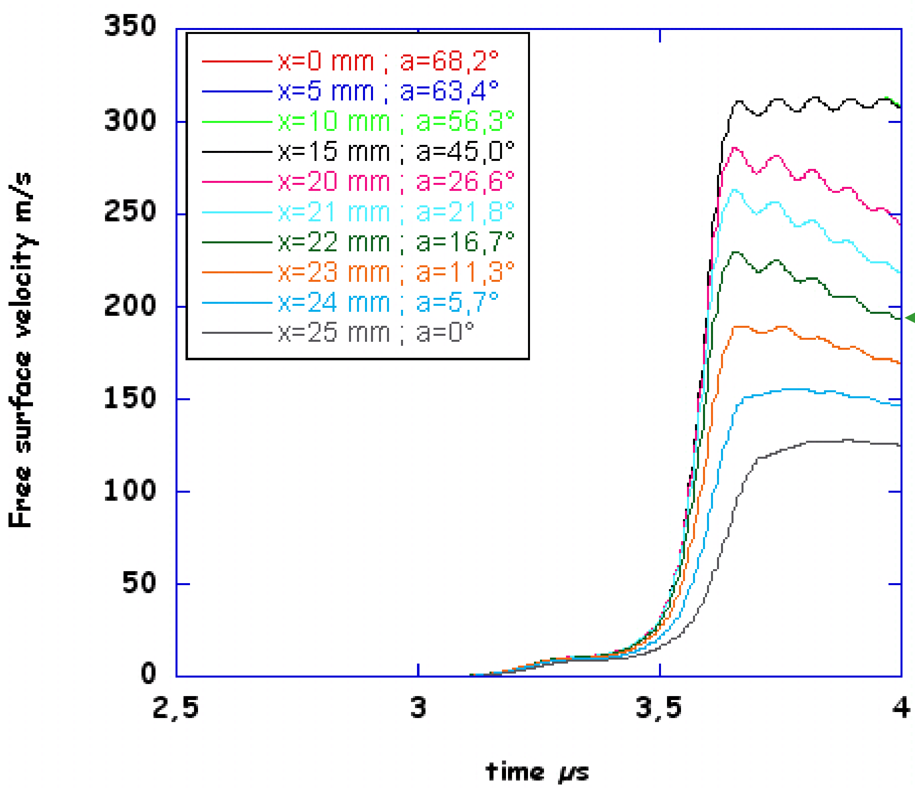


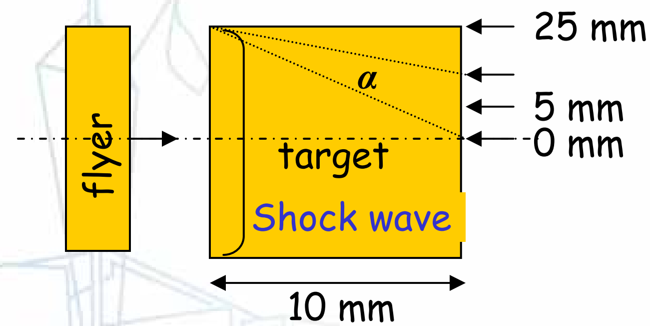


Fairly good agreement

Free surface velocity refinement

- Determination of the Angle of attenuation :





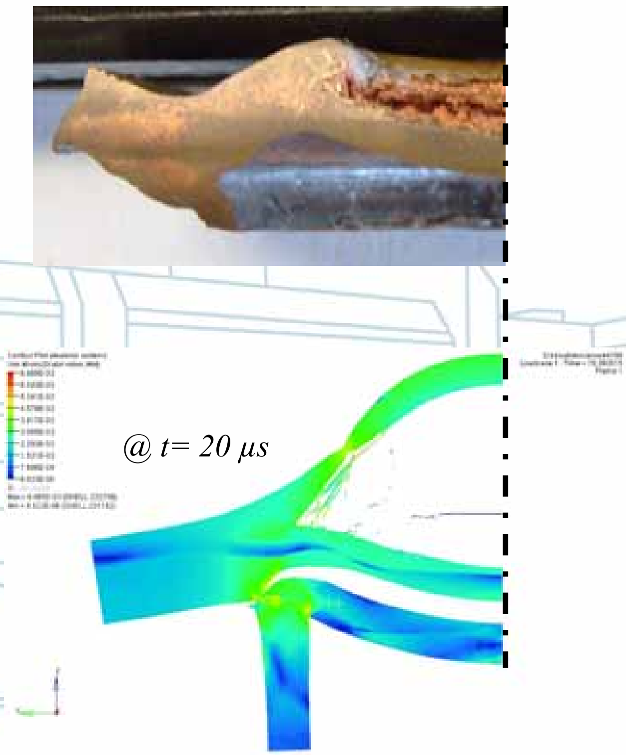
Shock front is detaching

=> 16.7° < α < 21.8°

In agreement with the analytical approach.

Fracture analysis

- Target deformation with pressure field



Conclusion

- The Tuler-Butcher criterion is able to reproduce dynamic fracture in plate impact condition on OFHC Copper (σ_r = *7.375 kbar; K = 20; A =1.81*).
- The angle of attenuation at 312 m/s in OFHC Copper has been estimated by experiments that are in agreement with theory and simulation. We found 16.7° < α < 21.8°.
- Refined experiments could be performed in ordre to refine this result.
- Other shock intensities and other materials should be tested.

States significance of this work

- Good accordance Exp/Num for velocity signals as well as for the target deformation.

- Inverse approach allows the estimation of the angle of attenuation when it is difficult to measure by experiments.

Acknowledgements

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Questions ?