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Résumé - Avec un canon à gaz léger une série d'expériences a été réalisée afin de déterminer les positions relatives de l'hugoniot et de quelques isentropiques de détente du cuivre.

Les instants de fonctionnement des soixante douze sondes utilisées à chaque expérience sont enregistrés par un multichronomètre digital.

Dans le domaine expérimental couvert 70 GPa - 150 GPa les résultats des points de l'isentropique du cuivre , dans le plan pression - vitesse matérielle, obtenus pour l'aluminium et le magnésium se situent "au-dessous" de la polaire de choc du cuivre du projectile.

Lorsque la pression de choc dans le cuivre augmente - de 70 GPa à 150 GPa - l'écart - en vitesse matière - entre ces deux courbes décroît régulièrement de 100 m/s à 15 m/s.

Abstract - With a two stage light gas gun, experiments have been performed in order to compare the hugoniot curve and some isentropic release curves of copper.

The working times of the seventy two pins used at each shot are recorded with a digital multichannel chronometer.

In the 70 GPa - 150 GPa experimental range, the isentropic results from Al and Mg targets , in the pressure - material velocity diagram, are "under" the copper shock polar of the projectile.

In this range, when increasing the copper shock pressure, the material velocity discrepancy (between the two curves) decreases from 100 m/s to 15 m/s.

1. INTRODUCTION

To compare, with great accuracy, the shock polar curve and some isentropic release curves in copper, we designed experiments to measure, on the same shot, four points on each of these curves in the pressure - material velocity diagram.

The principle of these experiments is shown on fig. 1. A copper projectile impacts a target made of two groups of sectors (fig 1a). The first group consists of three sectors Al, Mg and Cu, and the second one of six sectors. With each shock pressure induced in each of these sectors can be associated a point in the pressure - material velocity diagram (fig 1b).

As everyone knows, the discrepancies between the points 2 and 6 (on Mg shock polar), 3 and 5 (on Al shock polar) are very small, but more important between 1 (projectile velocity) and 7 (free surface velocity).

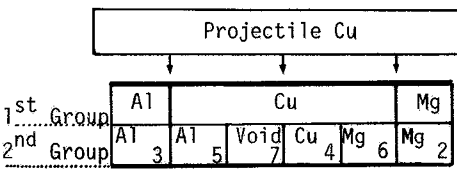


Fig 1a

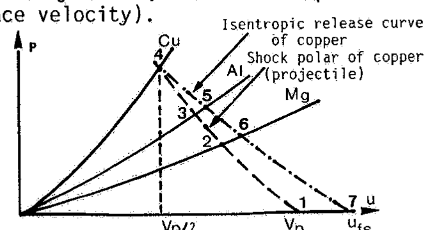


Fig 1b

2. EXPERIMENTAL DESIGN

2.1 - The launcher - The two stage light gas gun used for these experiments is located at the Centre d'Etudes de Vaujours. Its projectile velocity range is from 1,5 to 5 km/s with helium as propellant gas. The front face of the projectile - 80 mm caliber - is a copper disc (Ø 77 mm, 10 mm thick).

2.2 - The target - For the first group of sectors, the thickness, depending on the shot, is about 1,5 mm. For the second group, the thickness is 4,5 mm. All the pieces are controlled after lapping. The thickness accuracy is better than ± 2 µm.

In these experiments, copper used is electrolytic OFHC (99,95 % Cu), Al is pure aluminium (A9 - 99,99 %). Mg is almost pure (99,3 % Mg - 0,6 % Zr).

2.3 - The measurement method - it has been described in [1]. Seventy two shorting cap pins are coupled with an electronic digital multi-channel chronometer. (80 channels ± 100 ps) at each shot. Figure 2 shows the general arrangement of the pins. (Levels 1-2 → V_p ; Levels 3-4 → U shock velocities).

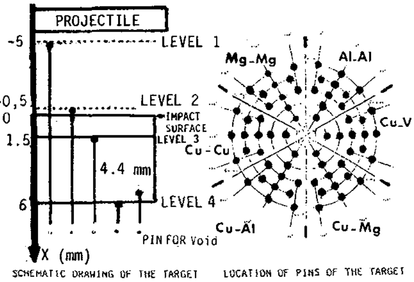


Figure 2

3. THE DATA ANALYSIS

Using the same least squares method as in [1], we get the projectile velocity with tilt angle and all the rough shock velocities in all the sectors. Refinements taking into account the distorsion of these shock fronts (festoon, horse saddle shape) give the corrected velocities. Detailed comparisons between various calculated distorsions provide a strong analysis on the real shape of the shock front and a control of the calculations, but for this, an important work is needed.

For Cu, Al and Mg, the shock polars used in the calculations are deduced from the linear relations U(u) shock velocity - material velocity :

Cu $\rho_0 = 8{,}930\ t/m^3$ $U = 3.941 + 1.497\ u$ (m/s) [1]

Al $\rho_0 = 2.705$ " $U = 5.380 + 1.337\ u$ (m/s) [2]

Mg $\rho_0 = 1.748$ " $U = 4.410 + 1.27\ u$ (m/s) [3]

The accuracy of this type of experiments generally is better than 1 %. But, locally, this accuracy is strongly dependent on the distorsions. After a detailed analysis of these distorsions the final coherency is in the range 1 ‰ - 8 ‰ for all the results although it doesn't follow from any step of the method. Table 1 reports these values.

Shot n°	ϵ	$V_{p(1)}$	Cu (4)		Al (3)		Al (5)		Mg (2)		Mg (6)		u_{fs} (7)
			P	u	P	u	P	u	P	u	P	u	
1	0,10	2713	72,3	1357	39,7	1863	37,8	1796	26,4	2123	25,3	2058	2756
2	2,23	3022	84,0	1516	46,3	2094	44,2	2022	30,9	2373	29,4	2299	-
3	0,72	4042	125,7	2021	67,7	2759	66,1	2715	44,7	3073	43,5	3018	-
4	1,72	4170	130,4	2073	70,5	2841	69,7	2817	47,1	3183	46,4	3152	-
5	0,55	4521	147,5	2257	79,1	3078	78,5	3063	52,2	3415	51,9	3401	4640

ϵ tilt angle (in degrees) - V_p projectile velocity (m/s). Numbers near V_p, Cu, Al, Mg, u_{fs} refer to points on diagram fig 1a; P pressure (in GPa); u mass velocity (m/s)

Table 1 - Experimental results

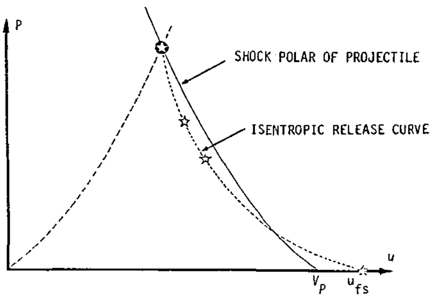
4. DISCUSSION OF THE RESULTS

4.1 - The discrepancy between projectile shock polar and release curves.

This type of experiment is not self-consistent. So, other data and assumptions are necessary to discuss these results.

From Table 1, all the Al (Mg) points, in p, u, diagram, on the release curves of copper avec located "under" the corresponding copper shock point, on the Al (Mg) shock polar. Secondly, the distance between each couple of points on the Al (Mg) shock polar, decreases when the copper shock pressure increases, And finally, this distance seems almost the same for a same release wave (comparison between Δu (Al) and Δu (Mg) from a same shot). In conclusion, from these results the copper release curves have the shape shown on fig. 3.

In order to improve these comparisons, the discrepancy Δu between the release wave curve and the projectile shock polar was calculated for a same pressure. Three ways were used each of them obtained from an independant experimental result, but unfortunately the accuracy of these results is very bad, decreasing as Δu decreases. Only, one can say that the values of Δu bear out the previous results.



COMPARISON BETWEEN SHOCK POLAR AND ISENTROPIC RELEASE CURVES IN THE PRESSURE - MATERIAL VELOCITY DIAGRAM

Figure 3

4.2 - How to explain these results ?

Several models may be suggested to explain these results such as classic elastic-plastic, elastic viscoplastic, with time relaxation, with temperature, viscosity or strain-rate dependance....

As first approximation, we'll try the classic elasto-plastic model, on Al results.

Assuming, as first approximation that a) this elastic-plastic behaviour obeys the Von Mises criterion b) Δu is the consequence of an elastic unloading stage of copper c) the plastic release curve can be deduced from the projectile shock polar by a translation of Δu, it is possible to calculate the pressure jump Δp between the shock pressure in copper and the beginning of the plastic release wave if one knows the material velocity jump corresponding to the elastic release [4].

The yield strength Y is correlated to ΔP, with our assumptions, by the relation $\Delta P = 2\,\frac{(1-\nu)}{1-2\nu}Y$. To calculate Y, it is necessary to make some assumptions on ν, Poisson's ratio : a) ν is a function of pressure [5] , b) the variation of gamma-Gruneïsen coefficient is a function of density, given by $\rho_0 . \Gamma_0 = \rho . \Gamma$ [5].

Using these assumptions for russian experimental results [6] [7] on copper, a linear ν (P) relation is obtained, in very good agreement with each of the results

$$\nu = 0,3445 + 7,5317.10^{-4}\ P\ (\mathrm{GPa})$$

(This relation gives, for ν = 0,5 the value of 206,4 GPa (2,064 Mb), to compare with Urlin melting calculations (205 GPa) [8]

About the material velocity jump corresponding to the elastic release Δu_e, the simplest assumption is that this jump is small enough to be chosen equal to zero. (Figure 4 - First assumption). Table 2 gives the the so obtained results, (russian results are also reported).

These results for ΔP and Y are too small in comparison with [6] and [7]. So is it necessary to make other assumptions to calculate the Δu jump during the elastic release (second assumption Fig. 4b) :

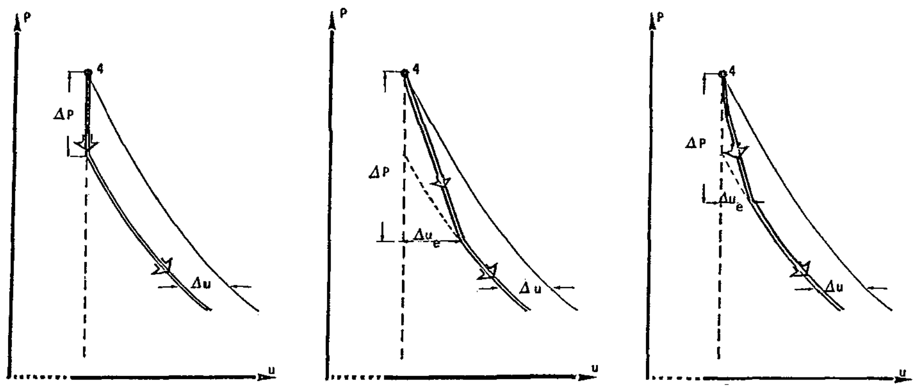
- or using the relation $\Delta p = \rho . C_e . \Delta u$ (ρ is the density, and C_e the elastic wave velocity),the results for ΔP and Y are too important.

- or using the volume jump during the elastic release, and introducing the Young modulus (E). To get results in accordance with the published results needs to multiply E by a factor 3 or 4.

So our suggestion is (Fig. 4.3 third assumption) that the elastic release necessarily begins with a decrease of pressure without a significant material velocity jump. As example, a rough calculation for the point near 85 GPa gives a pressure decrease of 3,8 GPa ($\sim \Delta P/4$) with no material velocity jump assumption.

	P GPa	$\overline{\Delta u}$ m/s	ΔP GPa	ν	Y GPa	Observations
Russian [6]	34	-	9	0,3699	1,858	ν values calculated
Results [6]	86	-	15	0,4099	2,290	from assumptions des-
[7]	122	-	10 ± 2	0,4361	1,134	cribed in this paper.
This	72,3	99	6,95	0,3989	1,168	ν calculated from
study	84,0	76	5,68	0,4077	0,884	linear relation given
with	125,7	60	5,30	0,4391	0,574	in this paper. $\overline{\Delta u}$ is
$\Delta u_e = 0$	130,4	35	3,15	0,4427	0,323	the mean value of Δu
	147,5	15	1,43	0,4555	0,116	calculated by three independent ways.

Table 2



FIRST ASSUMPTION $\Delta u_e = 0$ SECOND ASSUMPTION THIRD ASSUMPTION

THREE ASSUMPTIONS FOR THE BEGINNING OF THE RELEASE CURVE IN THE (P,u) DIAGRAM

Figure 4

5. CONCLUSION

The release curves in copper between 70 GPa and 150 GPa are under the Cu projectile shock polar for Al and Mg impacts. As a suggestion to interpret these results, a pressure decrease could take place before the elastic release. But other experiments with other materials are needed to confirm these first results.

6. ACKNOWLEDGMENTS

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