ELASTIC-PLASTIC BEHAVIOUR OF IRON AT HIGH STRAIN RATES AND ELEVATED TEMPERATURES

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Résumé : Des essais d'impact de plaques ont été réalisés pour étudier le comportement élastique-plastique d'un fer pur dans une gamme de vitesse de déformation allant de $10^4 s^{-1}$ à $10^6 s^{-1}$ et pour des températures comprises entre 20°C et 500°C. La contrainte maximale atteinte dans les échantillons est de 60 kbar. Les comparaisons expérience-calcul montrent que 1) la limite d'écoulement et le module de cisaillement de ce matériau sont des fonctions décroissantes de la pression, 2) l'influence de la température sur le module de cisaillement est négligeable devant celle de la pression.

Abstract : Plate-impact experiments were used to investigate the elastic-plastic response of pure iron at strain rates ranging from $10^4 s^{-1}$ to $10^6 s^{-1}$ and temperatures ranging from 20°C to 500°C. Maximal stresses in the specimens are 60 kbar. Comparisons between calculations and experiments show that 1) the yield strength and the shear modulus of this material are decreasing functions of compression, 2) the temperature dependance of the shear modulus is negligible relatively to its pressure dependance.

1 - INTRODUCTION

In the study of terminal ballistics, hydrodynamic computer codes are increasingly used to simulate phenomena encountered, for they give access to the evolutions of the physical parameters of the materials under examination. Nevertheless,the validity of the informations obtained depends on the mathematical models used to characterize the materials. The object of this paper is to determine the constitutive model of a 99.8 % pure iron, using static tensile tests and plate impact tests data. The constitutive model chosen is inspired by Steinberg's model which accounts for work hardening, pressure and temperature dependance of the yield strength and the shear modulus. The procedure is to identify the parameters of the constitutive model from the test data and then to verify its validity by comparison between experiment and calculation. This last stage is realized on recompression profiles obtained during plate impact experiments.

2 - TEST DATA

The iron used for this study was supplied in the form of 1000 x 1000 x 6 mm^3 plates obtained by hot rolling. The material has a 99.8 % purity, a density of 7.850 g/cm^3 and a mean grain size of 30 µm. Measurements carried out on this iron at 20°C and atmospheric pressure produced the following results /1/ /2/ :

- hardness : 91 HV10
- longitudinal and shear wave velocities :

$$C_L = 5944 \text{ m/s}$$
$$C_S = 3244 \text{ m/s}$$

The experimental data were obtained from plate impact tests for strain rates of between $10^4 s^{-1}$ and $10^6 s^{-1}$ and temperatures from 20°C to 500°C. Plate impact tests were performed at the Centre d'Etudes de Gramat by means of a compressed gas gun /3/. The experimental configuration is shown on figure 1. During these tests, measurements consisted of recording the impact velocity by means of three self shorting pins and the free surface velocity of the target with a Doppler Laser VISAR interferometer /4/, /5/. The parameters of the nine plate impact tests performed on the iron are given in table I. The different strain rates were achieved by using ramp

Table I : Summary of experiments.

Experiment N°	Impactor thickness (mm)	Specimen thickness (mm)	Buffer thickness (mm)	Impact velocity (m/s)	Initial temperature (°C)
1007	15	5.60		488	20
1008	15	5.66	30.03	555	20
1009	15	5.69	20.05	556	20
1010	15	5.70	5.07	558	20
1011	15	5.71		555	500
1012	15	5.79		494	300
1013	15	5.72		500	200
1015	15	5.69		487	107
1016	15	5.69		492	150

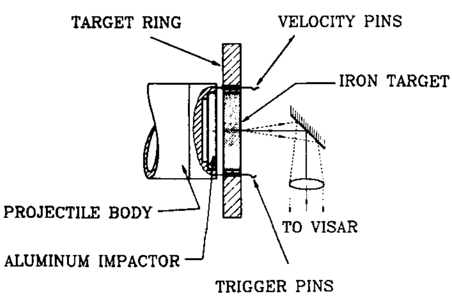

Figure 1 - Schematic of the plate-impact configuration.

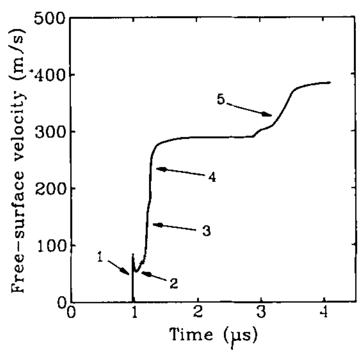

Figure 2 - Free-surface velocity history of experiment 1007.

wave buffers in front of the iron samples. An induction heating device was used for temperature experiments.

All the free surface velocity profiles were characterized by five peculiarities, as exemplified by the profile of the figure 2 :

- elastic precursor (1)
- decrease (2) behind the elastic precursor
- reflection of the elastic precursor on the plastic wave (3)
- plastic wave (4)
- recompression wave (5) due to the experimental configuration chosen.

The decrease behind the elastic precursor has already been observed by Johnson and Rohde /6/ on an Armco iron and seems therefore to be a characteristic of this materials. According to these authors this phenomenom corresponds to the formation of twins at the elastic-plastic transition of the iron.
The results of the plate-impact tests are given graphically in figures 3 et 4. On each of these figures, we have noted the elastic limits corresponding to the maximal values of the elastic precursor and to the minimal values of the decrease behind the elastic precursor. By analogy with static tensile tests these values are defined respectively as the upper and lower elastic limits. Figure 3 shows that the

dependance of the upper and lower elastic limits of iron according to temperature are quasi-linear between 20°C et 500°C. The ratio between the elastic limits at 500°C and at 20°C is identical for higher and lower values and is equal to 0.67. If we extrapolate the two straight lines for an elastic limit of zero, we find temperature of 1546°C et 1525°C which are close to iron's melt temperature 1538°C. This observation suggests a linear fall to melt temperature, a hypothesis which remains to be confirmed by tests at more than 500°C.
In addition to results obtained during plate impact tests, figure 4 shows the point obtained during a static tensile test /1/, the points obtained with a Hopkinson bar device on the same iron /7/ and the results obtained by Klopp et al. /8/ on a 99.99 % pure iron. As in the case of plate impact tests, Hopkinson bar tests yield data showing a higher and a lower peculiarity during the first deformations. It does not seem possible to assimilate strictly these points to the higher and lower elastic limits, for, as we have underlined in a previous publication /9/, Hopkinson bar devices do not allow measurement of elastic limits of materials in uniaxial stress for strain rates above $10^3 s^{-1}$. In fact, the exploitation of the Hopkinson bar data presupposes a homogeneous strain and a one dimensionnal stress state, hypotheses that are not justified during the first deformations. Although the points measured with the Hopkinson bar device do not correspond to elastic limits, it is clear from figure 4 that they fall on a curve parallel to that obtained by Klopp et al.

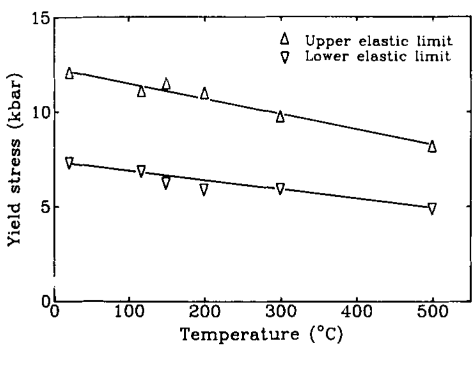

Figure 3 - Temperature sensitivity of the upper and lower elastic limits of iron from plate-impact experiments. Strain rate is about $10^6 s^{-1}$.

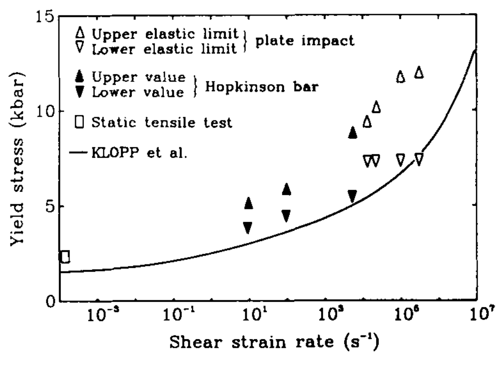

Figure 4 - Strain rate sensitivity of the upper and lower yield stresses of iron at 20°C. The x axis is a logarithmic scale.

3 - MODELISATION

The objective of the constitutive equation chosen is to describe the elastic-plastic transition of iron for strain rates above $10^4 s^{-1}$, maximal stresses of 60 kbar and temperatures of between 20°C and 500°C. We will not consider the decrease behind the elastic precursor observed experimentally, which requires the development of an elastic-viscoplastic law. Nor will we consider the influence of the strain rate on the yield strength because experiment has shown that lower elastic limit remains constant for strain rate above 10^4 s^{-1} (figure 4).
The model chosen is inspired by the model elaborated by Steinberg et al. /10/ which expresses the variations of the yield strength Y (in the Von Mises sense) and the shear modulus G as functions of the equivalent plastic strain ε_p, the pressure P

and the temperature T :

$$Y = \left[Y_0 + \beta(\varepsilon_p)^n\right]\left[1 + \frac{Y'_p}{Y_0}P - \frac{Y'_T}{Y_0}T\right]$$

$$G = G_0\left[1 + \frac{G'_p}{G_0}P - \frac{G'_T}{G_0}T\right]$$

The subscript O refers to the reference state (T = 20°C, P = 0 kbar). Primed parameters with the subscripts P and T imply derivatives of that parameter with respect to pressure or temperature at the reference state. The yield stress Y_0 is determined from the lower value of the Hugoniot Elastic Limit and the work-hardening parameters β and n from static tensile test result. The value of the shear modulus G_0 is obtained from ultrasonic measurement. The parameter Y'_T is determined from the data of figure 3. These constants are presented in table II. The parameters Y'_p, G'_p and G'_T are calculated in the next section to give the best fit between experimental and calculated free surface velocity profiles.

Table II : Numerical values of elastic-plastic parameters.

Y_0 (kbar)	G_0 (kbar)	β (kbar)	n	Y'_T (kbar/°C)
7.4	826	2.8	0.35	- 0,005

4 - COMPARISON BETWEEN DATA AND CALCULATION

Plate-impact simulations were performed with the hydrodynamic computer code MONO-DIM. A Mie-Grüneisen equation of state was adopted to describe the volumetric compressionnal behaviour of iron.The method presented by Gust /11/ was used for calculating the cold energy and temperature from this equation of state. The numerical values of parameters for iron are indicated in table III.
Firstly, we have simulated experimental data of shots 1007, 1008 and 1009 with the parameters Y'_p, G'_p and G'_T fixed to zero. Comparisons between calculations and experiments (figure 5) show that the initial recompression wave arrives too early and that the shape of this wave does not agree with the data. Similar remarks were carried out by Barker and Hollenbach /12/ on release wave of an Armco iron initially shocked at 103 kbar. To achieve the good fit of the data, the yield strength in

Table III : Numerical values for Mie-Grüneisen E.O.S.

Initial density (g/cm³)	C_0[1] (m/s)	S[1]	Grüneisen parameter	Specific heat (J/Kg/°C)	Ref.
7.850	4630	1.33	1.7	452	/12/

[1] *linear shock velocity, particle velocity relation :* $U = C_0 + su$

their calculations was made a decreasing function of the compression, the Poisson's ratio an increasing function of the compression and a large Bauschinger effect was assumed. They pointed out that Armco iron under stress of 100 kbar shows a tendancy toward hydrostatic behaviour. The values of parameters Y'_p and G'_p corresponding to their model are respectively - 0.032 and - 3.5.

In our case, the best fit of the data is achieved with Y'_p = - 0.042, G'_p = - 8.0 and a Bauschinger model inspired by Cochran and Guinan /13/. Figure 5 shows the good agreement between calculations and experiments on the recompression profiles.

We now turn to the influence of initial temperature on the wave propagation with calculations of shot 1011, 1012 and 1015. Comparisons between experimental data and calculations performed with the parameter G'_T fixed at zero (figure 6) show that the total recompression profiles are properly reproduced. That means that the temperature dependance of the shear modulus of the iron is negligible relatively to its pressure dependance during dynamic sollicitation at 60 kbar.

The values of parameters G'_p and G'_T achieved to obtain the good fit of plate-impact data disagree with the corresponding static data. For exemple, Guinan and Steinberg /14/ give G'_p = 1.8 and G'_T = - 0,42 kbar/°C for polycrystalline iron. As pointed out by Barker and Hollenbach /13/, the material behind the plastic wave is in a chaotic state with a large amount of twins. This would explain the disagreement between static and dynamic values of G'_p and G'_T for iron. In addition we note that the relations $Y'_p/Y_0 = G'_p/G_0$ and $Y'_T/Y_0 = G'_T/G_0$ are not valid for this material.

5 - CONCLUSIONS

The elastic-plastic behaviour of a pure iron has been determined over the temperature range of 20°-500°C, the strain-rate range of 10^4-$10^6 S^{-1}$ and for a maximal stress of 60 kbar by plate-impact experiments. The yield strength decreases linearly from a 20°C value of 7.4 kbar to about 5 kbar at 500°C. Comparisons between calculations and experiments have shown that the yield strength and the shear modulus of this material are decreasing functions of compression and that the temperature dependance of the shear modulus is negligible relatively to its pressure dependance. The disagreement between these results and corresponding static results are interpreted by the fact that iron is in a chaotic state behind the plastic wave.

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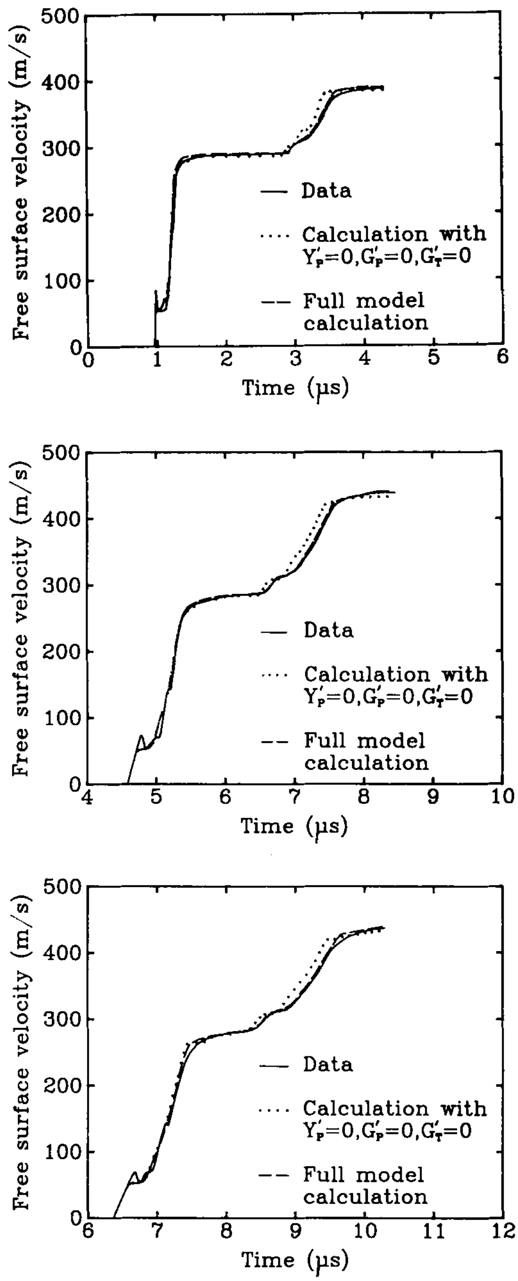

Figure 5 - Comparison between calculations and experiments.
- a) shot 1007 - b) shot 1009 - c) shot 1008

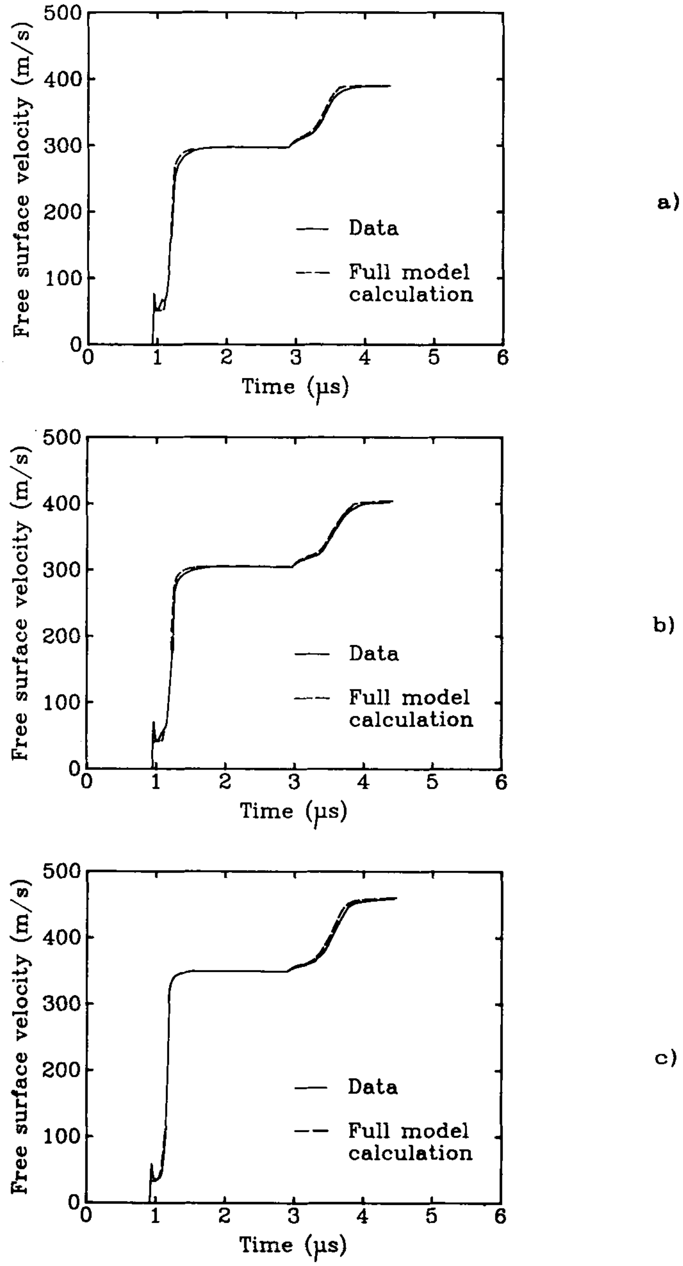

Figure 6 - Comparison between calculations and experiments.
- a) shot 1015 - b) shot 1012 - c) shot 1011