Dynamic damage in metal: porosity as a test for damage models

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Impact Engineering and Application
Akira Chiba, Shinji Tanimura and Kazuyuki Hokamoto (Eds)

DYNAMIC DAMAGE IN METAL : POROSITY AS A TEST FOR DAMAGE MODELS

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ABSTRACT

Shocks can generate high strain rates (from 10^4 to 10^6 s^{-1}) in metals, and can damage the sample up to the point of spallation. In ductile metals, the main damage mechanism is nucleation, growth and coalescence of pores. This paper presents microtomography measurements of porosity in shocked samples, made at the European Synchrotron Radiation Facility. The measurements are compared to the predictions of a damage model based on a recent viscoplastic extension of the Gurson model. It is found that the porosity level predicted by the model in a plate impact configuration disagrees with the measurements, though the free-surface-velocity curves are well captured by the model.

KEYWORDS

Damage, plate impact, shock wave, porosity, high strain rate, viscoplasticity, tomography X.

INTRODUCTION

The study of dynamic damage in plate-impact experiments is made difficult by the complexity of the mechanical and metallurgical phenomena at play, and also because of the short duration of the experiments. This presentation focuses on the analysis of impact experiments leading to damage in Cu and Ta samples, where the strain rates $d\varepsilon/dt$ range from $10^5 s^{-1}$ to $10^7 s$. A spall state is not reached in the experiments considered here.

A standard diagnosis in such experiments consists in real-time free-surface velocity (fsv) measurements. Besides, the history of the sample during the experiment reflects itself in its inner damage distribution. At the present time, porosity measurements can be performed only after the shocked samples are recovered. Both the fsv and the porosity are quantities accessible from numerical computation with finite-element codes containing some constitutive model allowing for microstructure evolution. Most often, the latter is accounted for by a local time-dependent porosity state variable. Thus the above two diagnoses can be used as a test to dynamic damage models, Zurek *et al.* (1997), Thissel et al., (2000). However, the local porosity is not an easy quantity to measure, and usual techniques, Zurek *et al.* (1997), consisting in micrography examination of 2D cuts in the samples may lead to imprecise data, either due to alterations of the porosity because of the surface treatment (polishing and etching), or to the very process of extrapolating the results to 3D from an insufficient number of cuts, which may involve additional imprecisions. Here, we use X-Ray tomography, which allows for a direct 3D reconstruction of the porosity distribution.

Our purpose is to confirm that such porosity measurements constitute a very stringent test to damage models, whereas fsv measurements prove to be insufficient. We first present the plate impact experiments, and discuss comparisons of fsv curves with that obtained from a suitably modified Gurson model. The X-Ray tomography measurements are presented next, and the porosity is compared to that predicted by our model.

PLATE-IMPACT EXPERIMENTS AND NUMERICAL CALCULATIONS

The experiments are carried out with a powder gun, with Al projectiles and Cu or Ta targets. The projectile velocity is measured by means of piezo-electric pins (fig. 1), whereas the fsv is measured with a Fabry-Pérot Doppler Laser Interferometer (DLI) system, the time resolution of which is sufficient for such experiments. The DLI position is 30° (fig. 2) off from the gun axis. This angle allows for sample recovery without additional damage due to subsequent shock with the measuring device.

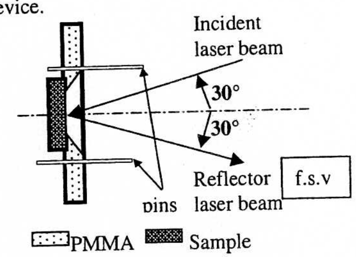

Figure 1. Target in the plate impact experiment

Figure 2. Microscopic observation of pore clusters in a cut Ta sample.

The shock levels observed range from 5 to 15 GPa, with durations ranging from 200 to 1000 ns. We report in Figure 3 the fsv curves obtained with one Al/CuC2 shot, and in Figure 4 the same quantity in three Al/Ta experiments. Note the different shock pressures and projectile thicknesses.

metals	Projectile velocity Vp (m/s)	projectile thickness (m)	target thickness (m)	Shock pressure max (Gpa)
Al / Cu	239	3.5 10^{-3}	3.9 10^{-3}	2.5
Al / Ta	570	2. 10^{-3}	3.9 10^{-3}	6
Al / Ta	1039	0.5 10^{-3}	3.9 10^{-3}	8.7
Al / Ta	1078	1. 10^{-3}	3.9 10^{-3}	13

Table 1. Plate impact experiment characteristics.

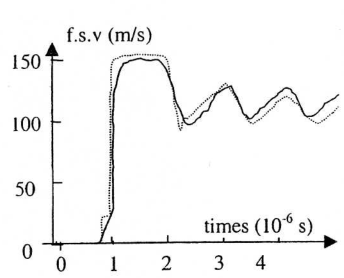

Figure 3. Fsv curve in Cu.

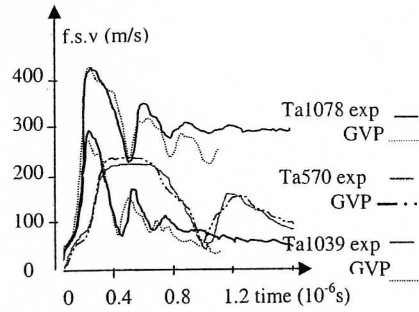

Figure 4. Fsv curve in Ta.

The experimental fsv curves are compared to curves computed from a pore growth model consisting in a Bingham viscoplatic extension of the Gurson model, Perrin (2001), consistently coupled to elasticity, Arnould *et al.* (2001). The parameters of the model are that of the bulk Bingham law (the flow stress Y_0, the viscosity η), the elastic constants of the metal (taken from the literature), and an initial porosity f_0 which represents the porosity at the end of the nucleation step (one possible origin of which being cavitation, i.e. energetically favorable unstable release of stored elastic energy). Only subsequent growth is decribed by the model (and also the final coalescence step, described by Tvergaard's porosity accelerator trick, but not used here). This constitutive model is implemented in a finite-element hydrodynamic code. The flow stress, the viscosity, and the initial porosity are deduced from a fit to the experimental fsv curves, for each material. We find that these experimental curves are well reproduced from a single set of parameters for each material, irrespective of the characteristics of the experiments. The higher value of the initial porosity required for Cu may indicate that this material is more easily damaged than Ta. Comparison to fsv curves thus seem to validate the model so far. We now use an independent check, namely that provided by porosity measurements by means of X-Ray tomography.

Model parameters	Initial porosity f_0	Flow stress Y_0 (Pa)	Viscosity η (Pa.s)
Copper	3. 10^{-4}	220. 10^{6}	55.
Tantalum	1. 10^{-6}	900. 10^{6}	30.

Table 2. Parameters of the viscoplastic Gurson model for Cu and Ta

TOMOGRAPHY MEASUREMENTS

The X-ray tomography measurements presented hereafter have been carried out on the ID-19 beamline of the European Synchrotron Radiation Facility (ESRF), a third generation X-Ray synchrotron, Baruchel *et al.* (2000). We report here results for Cu only, Ta samples still being under investigation.

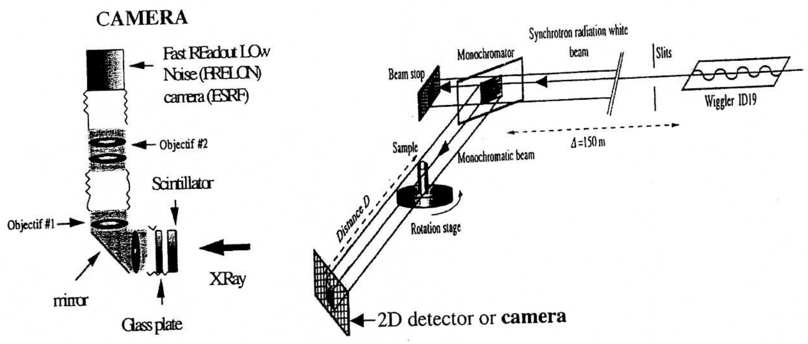

Figure n° 5 : ESRF ID19 experimental set up

The proportion of transmitted photons is estimated from the absorption curve of each material, according to Lambert's law, as a function of the absorption coefficient, the sample thickness, and the beam energy. The goal here is to optimize these three parameters in order to arrive at a contrasted picture with as many visible details as possible. For Cu, typical pore sizes are in the range 1.-100. μm. The beam energy is 55 Kev, the sample thickness is 1.4 mm, and the transmission is 12 percent. For a denser material such as Ta, a compromise has to be found between energy and sample thickness. Working with the same energy requires a smaller thickness. However, the thickness has to remain sufficient so as to constitute a reasonable statistical sampling of the pore distribution.

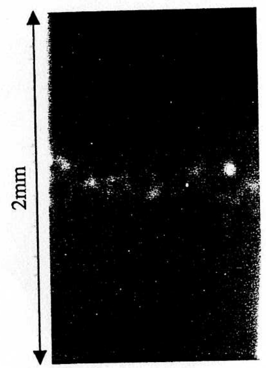

Fig.6. : Preliminary radiography.

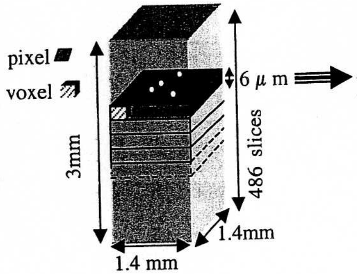

Fig. 7. : The reconstruction of the slices.

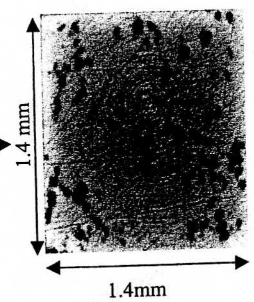

Fig 8.: Typical slice in the spall plan.

From the recovered shocked Cu sample are cut parallelepipeds (1.4 x 1.4 x 3.0 mm^3). A preliminary radiography (Fig. 6) is made first in order to check the position of the damaged zone, estimated by shock wave theory. The beam is then aimed at this zone, and 900 shots are taken under orientations differing by steps of 0.2° with a total acquisition time of 2,5 hours (fig. 5). These projections are reconstructed (Fig. 7) as 486 horizontal slices of 1024 x 1024 x 1 pixels (total reconstruction time : ~ 24 hours). The slices constitute virtual 2D images of thickness 6 μm, the spatial resolution of this measurement. We retained only 200 slices in the most porous region ("spall plane"), whose tiling constitute a 3D image of this region (Fig. 8). In the same slice appear clusters, and isolated pores.

COMPARISON BETWEEN PREDICTED AND MEASURED POROSITIES

With a suitable morphological treatment (fig. 8), we convert the original image in gray levels into a binary one, from which we deduce the porosity averaged over each slice, as a function of position along an axis orthogonal to the spall plane (fig. 10). In Fig.10 are also displayed porosity curves computed with the viscoplastic Gurson model, using the parameters of Fig. 3, at three different times.

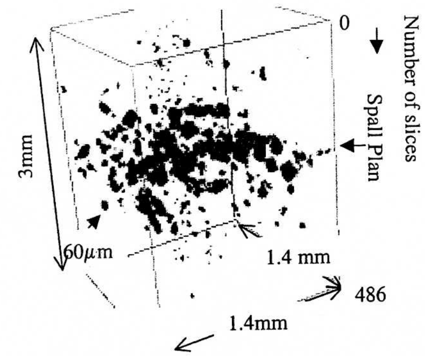

Figure 9. Visualization 3D in voxels of the spatial pores repartition of damage copper parallelepiped.

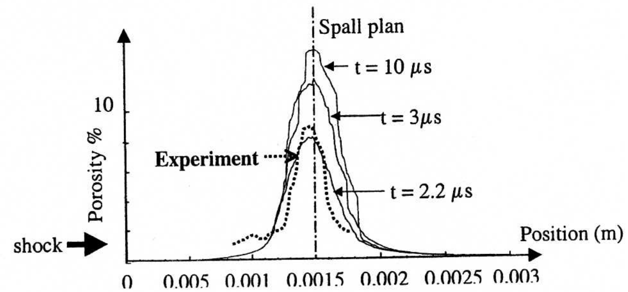

Fig 10. Porosity as a function of position. Experimental curve for the evolved porosity, compared to intermediate calculations with the viscoplastic Gurson model at three different times.

We observe that, contrary to what happens in the experiment, and in spite of a reasonably good adequacy between the theoretical and experimental fsv curves of Fig. 3, the porosity does not saturate in the model, and continues to grow. A similar behavior has been reported by Thissel at al. (2000), these authors using a different model. Note that on the other hand, the porosity predicted by our model in different conditions (initial pressure pulse reproducing that of laser shock experiments, Bontaz et coll. (2001) in these proceedings) reaches a stable level. Further investigations of the model, and of the pressure distributions which take place in experimental conditions are thus necessary to precise the origin of the discrepancy between numerical calculations and experimental measurements for plate impact experiments.

CONCLUSION

Predicting correct free surface velocity curves during the first stages of a plate impact experiment is not a sufficient criterion to establish the validity of a dynamic damage model. The prediction of the porosity level along the axis orthogonal to the spall plane has to be added as a more challenging test, as was noted by Zurek *et al.* (1997). In this perspective, X-Ray tomography appears as a promising technique for collecting statistical data on the porosity distribution in shocked samples, which may ultimately lead to a better understanding of the pore growth regime, and hopefully to an improvement of the models for dynamic damage.

ACKNOWLEDGEMENTS

Useful conversations with J.-P. Ansart and C. Denoual are acknowledged.

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Impact Engineering and Application
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AN ELASTO-PLASTIC IMPACT OF TWO BALLS

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ABSTRACT

This paper deals with elasto-plastic impact of two balls. Impacts of two balls are generally characterized by *Coefficients of Restitution* and the stress distributions of balls during impact are generally treated by *Hertzian* quasi-static elastic contact theory. However, *Coefficient of Restitution* is originally defined for point mass and *Hertzian* contact theory assumes extremely localized elastic deformation with small strains, while actual balls have a finite size and generally plastic deformation arise by impact. Present paper intends to discuss the applicability of *Coefficient of Restitution* for actual balls and investigate the effect of plastic deformation on the *Coefficient of Restitution* in direct central impact of two balls. Experiments of direct central impact of two balls are conducted for bearing steel balls (JIS SUJ2). The steel balls are impacted by pendulum motions. *Coefficients of Restitution are* estimated by measuring the angles of pendulum for both pre- and post- impact. Tensile tests are conducted for bar type test pieces to obtain mechanical properties of the SUJ2. The balls and the test pieces made of JIS-SUJ2 are annealed under the same condition. The mechanical properties are used in the finite element analyses. *Coefficients of Restitution* obtained from experiments and from F.E.M are compared. Then the coefficients of restitution are presented as the function of the impact velocities. Further, simulations are carried out to investigate the influences of ball size, yield stress and tangent modulus on coefficients of restitution.

KEYWORDS

elasto-plastic impact, impact of two balls, *Coefficient of Restitution,* F.E.M, plastic deformation, direct central impact.

INTRODUCTION

This paper deals with elasto-plastic impact of two balls. Impacts of two balls are generally characterized by Coefficients of Restitution. However, Coefficient of Restitution is originally defined for point mass. Generally, Hertzian quasi-static elastic contact theory (Hertz (1882)) is applied to the analysis of elastic impact of spheres (Timoshenko S. & Goodier N. (1970)). However, actual balls have a finite size and produce plastic deformation at even very low impact speed (Stronge W.J. (2000)). Present paper intends to discuss on the applicability of Coefficient of Restitution to actual balls and