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## Damage behaviour of alumina submitted to a divergent spherical wave

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**résumé :** L'efficacité des blindages en céramique dépend de la réponse du matériau face à la propagation de l'onde sphérique divergente générée par l'impact du projectile. Cet article propose une approche de modélisation de l'endommagement d'une alumine pure incluant les aspects expérimentaux, théoriques et numériques. Une technique de moyennisation est adaptée au cadre d'application, pour rendre compte de l'effet des endommagements locaux sur la réponse macroscopique du matériau. Des lois d'évolution empiriques simplifiées des endommagements sont calées sur des mesures expérimentales macroscopiques. Les possibilités de cette approche sont montrées par le biais de comparaisons expériences-calculs numériques unidimensionnels.

**abstract :** The efficiency of ceramic armors strongly depends on the behaviour of the material submitted to the propagation of the divergent spherical wave generated by the impact of the projectile. This paper deals with a modelling approach of the damage of an pure alumina including the experimental, theoretical and numerical aspects. An averaging technique is adapted to the application field, to take into account the effect of the local damages on the overall behaviour of the material. Simplified empirical damages evolution laws are fitted on macroscopical measurements. The capabilities of this approach are shown by means of comparisons between experiments and one-dimensional numerical calculations.

### 1. INTRODUCTION

At the impact of a projectile onto an armour, a divergent spherical wave propagates within the armour, followed by the slower mechanical penetration of the projectile. The efficiency of the armour is affected by the damage induced by the spherical divergent wave. This paper contributes to the understanding of the damage mechanisms in a pure alumina submitted to this type of loading. In a first part, the experiments performed on AL 23 alumina [1] are described and the associated phenomenological analysis [2] [3] is given as a basis for our modelling method. In a second part, the effects of the two types of observed damage, isotropic and anisotropic, are taken into account by means of an averaging technique [4]. This technique has been adapted to our numerical framework [5]. The last part of this paper is devoted to the fitting of simplified empirical damage evolution laws on the experiments and to the comparisons between experimental and calculated velocity-time profiles.

## 2. EXPERIMENTS AND LOADING PATHS

### 2.1. Experiments

Several experiments producing a longitudinal divergent spherical wave loading have been performed on AL 23 alumina specimens. These experiments consist in detonating half a sphere of HE explosive in contact to a decimetric material block [1]. Two types of experimental set up are used. The first one allows to measure the velocity-time profiles by an IDL interferometry technique (Figure 1b). Four experiments with different thicknesses ( $r_1 = 30$  mm,  $r_2 = 50$  mm,  $r_3 = 70$  mm,  $r_4 = 90$  mm) of alumina are displayed in Figure 4. The second experimental set up permits to the recovery of the specimen after the shock by means of a steel outer layer enclosing the explosive and the specimen (Figure 1a).

### 2.2. Loading evolution

If the behaviour of the material is perfectly elastic, each elementary volume is submitted to the following typical loading sequence (Figure 2). The first phase is a tri-compression in uniaxial strain state (Figure 2b), the following is a release in triaxial strain state (Figure 2c) with the evolution of hoop stresses to tensile mode (Figure 2d). Because of the divergent nature of the wave, the stress levels decrease in accordance with the distance  $r$  from the explosive location.

### 2.3. Damage description

During such dynamic tests, the real-time observation of damage mechanisms is not possible. The damage description must be done from the post-mortem analysis (final state of damage). For the AL23 alumina, this analysis leads to several visible networks of cracks (Figure 3a). Some of them issued from the boundary effects are not considered. The spherical divergent wave provides two types of cracks, intergranular randomly oriented cracks and transgranular radially oriented cracks [2]. The first ones are observed in a zone near the explosive location and their number decreases with the distance  $r$  from the explosive location. In this region, TEM investigations have shown a plastic deformation analogous to the observed one in plate impact soft recovery experiments [1]. The second ones appear far from the explosive location where the density of the other ones is low (Figure 3b).

## 3. PHENOMENOLOGICAL ANALYSIS

Based on the microscopical observations and macromechanical considerations, a chronology of damage has been proposed [2]. The plastic deformation of the grains of alumina and the intergranular cracking are associated to the phase of loading in uniaxial strain. No influence of the observed intergranular cracks has been seen on the experimental profiles [6]. The dependence of the density of cracks with the distance  $r$  to the explosive location is linked to the decrease of the stress level induced by the divergent nature of the wave. The transgranular cracking is nucleated by the tensile hoop stresses. These tensile stresses do not develop in a fully damaged material. It explains that the transgranular cracks appear only where the material is not already pulverized by the intergranular cracking.

## 4. MODELLING APPROACH

A plasticity model is used for the phase of loading [7]. To model the damage, our approach falls into four parts : the description of the damage state of the material, its evolution, the damage elasticity coupling and the numerical implementation.

### 4.1. The description of the damage state

For an easier calculation, the isotropic cracking is represented by a distribution of spherical voids. The macroscopical response is supposed to be similar to an isotropic distribution of slit cracks from a

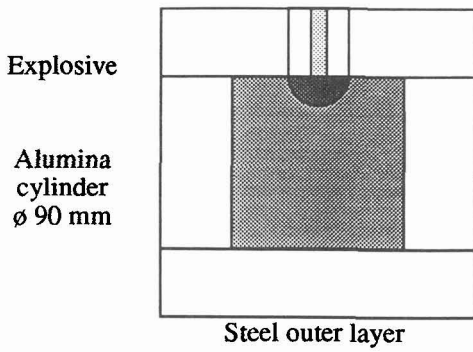


Figure 1a : Soft recovery experiment.

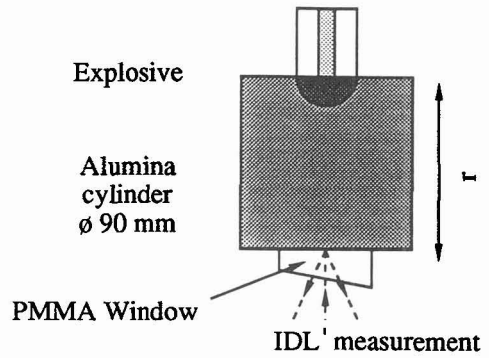


Figure 1b : Experiment with measurement.

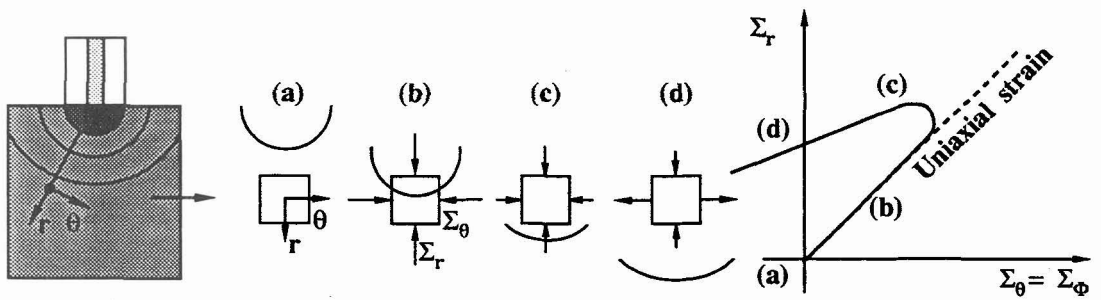


Figure 2 : Typical loading evolution for an elastic undamaged material.

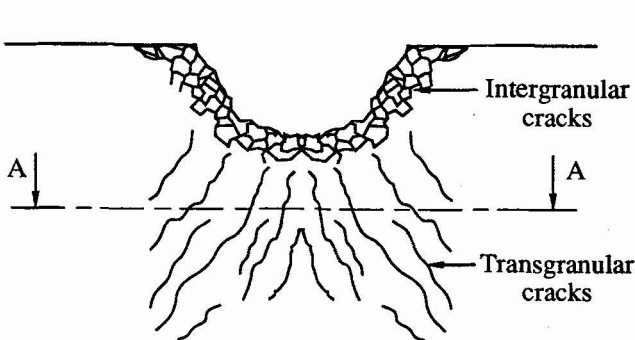


Figure 3a : Isotropic and anisotropic networks of cracks

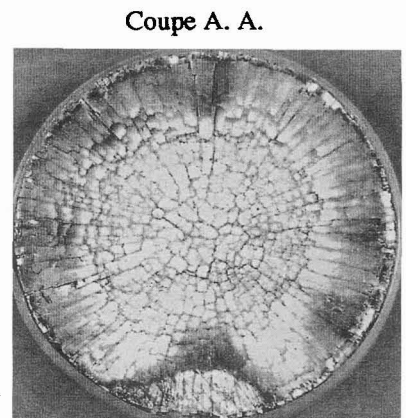


Figure 3b : Transgranular cracks in the soft recovered sample [1]

macroscopical point of view. The anisotropic cracking is represented by a distribution of penny-shaped cracks oriented in accordance with the observed cracks, the plan of each cracks containing the propagation axis of the wave.

#### 4.2. The damage evolution

A nucleation threshold  $\Sigma_{r1}$  for the isotropic damage is defined. When the axial stress becomes greater than  $\Sigma_{r1}$ , the passive nucleation of damage is set off. The damage becomes active during the release phase when the axial stress decreases and becomes lower than a threshold of activation  $\Sigma_{r2}$ . When this activation threshold is achieved, the volumic fraction of void rises with the following constant ratio by time step :

$$df = K_1 \Sigma_{\max}^{K_2} \quad (1)$$

This formulation permits to take into account the variation of the cracks density with the maximum applied radial stress  $\Sigma_{\max}$ . The nucleation and propagation of the anisotropic damage sets off when the hoop stresses become tensile. Then, the volumic fraction of void rises with the following constant ratio by time step :

$$df = K_3 \quad (2)$$

#### 4.3. Damage-elasticity coupling

Initially proposed by Mori and Tanaka [8], the model has been modified for brittle material with cracks [5]. The damaged material is represented by heterogeneities with no rigidity within an isotropic homogeneous elastic matrix. The perturbations of both overall stress field  $\Sigma$  and elastic strain field  $E$  by the heterogeneities are calculated in average on the representative elementary volume. The overall stress-strain relationship is given as following:

$$\Sigma = C_m \cdot \left( I + \frac{f}{1-f} Q \right)^{-1} \cdot E \quad (3)$$

where  $C_m$  is the matrix rigidity,  $I$  is the identity tensor,  $f$  is the volumic fraction of void,  $Q$  is the Hill localization tensor.

#### 4.4. Numerical implementation

The accuracy of the numerical calculations involves a small cell-size of discretization of the material. The size of the cell becomes equal or smaller than the size of the heterogeneities. The previous stress-strain relationship has to be introduced in each interval of the mesh, but the damage computations are performed on large companion-elements, associated to each interval of the mesh, homogeneous on the heterogeneity scale. For this type of calculation, it is convenient to use an incremental formulation for the overall stress-strain relationship, obtained by differentiation of (3):

$$\frac{d\Sigma}{dt} = C_m \cdot \left( I + \frac{f}{1-f} Q \right)^{-1} \cdot \left[ \frac{dE}{dt} + \frac{f}{(1-f)^2} Q \cdot \left( I + \frac{f}{1-f} Q \right)^{-1} \cdot E \cdot \frac{df}{dt} \right] \quad (4)$$

### 5. COMPARISONS BETWEEN NUMERICAL CALCULATIONS AND EXPERIMENTS

Because the lack of real-time observations, the results of the numerical calculations have been obtained by a fitting of the parameters of the damage evolution laws (Figure 4). The final values of these parameters are summarized in table 1. The loading phases of the four velocity-time profiles are correctly reproduced by the model of plasticity [7]. This result is a validation of the model in this geometry.

The profiles 1 and 2 correspond to measurements in the isotropic damage zone. The release phases of these profiles are quite good reproduced by the calculations. The calculated damage has an influence on the calculated loading paths in such a way that hoop stresses do not become tensile. The profiles 3 and 4 correspond to measurements in the anisotropic damage zone. The release phases are not so well reproduced. This result may be explained because of no transition zone between the isotropic damage and the anisotropic damage is taken into account. However, the calculated damage evolution induces the relaxation of the calculated tensile stresses.

These results show that the damage-elasticity coupling works satisfactorily in our numerical framework and can be a tool to identify the damage parameters. From a physical point of view, this modelling approach gives some promising results, despite of the use of a simplified description of the damage mechanisms. This method could be used to improve the model by an iterative comparison between experiments and numerical calculations.

Table 1 : Parameters of the numerical calculations

$\Sigma_{r1}$ (GPa)	$\Sigma_{r2}$ (GPa)	$K_1$ (Pa <sup>-2</sup> )	$K_2$	$K_3$
7	9	$5.10^{-27}$	2	$5.10^{-4}$

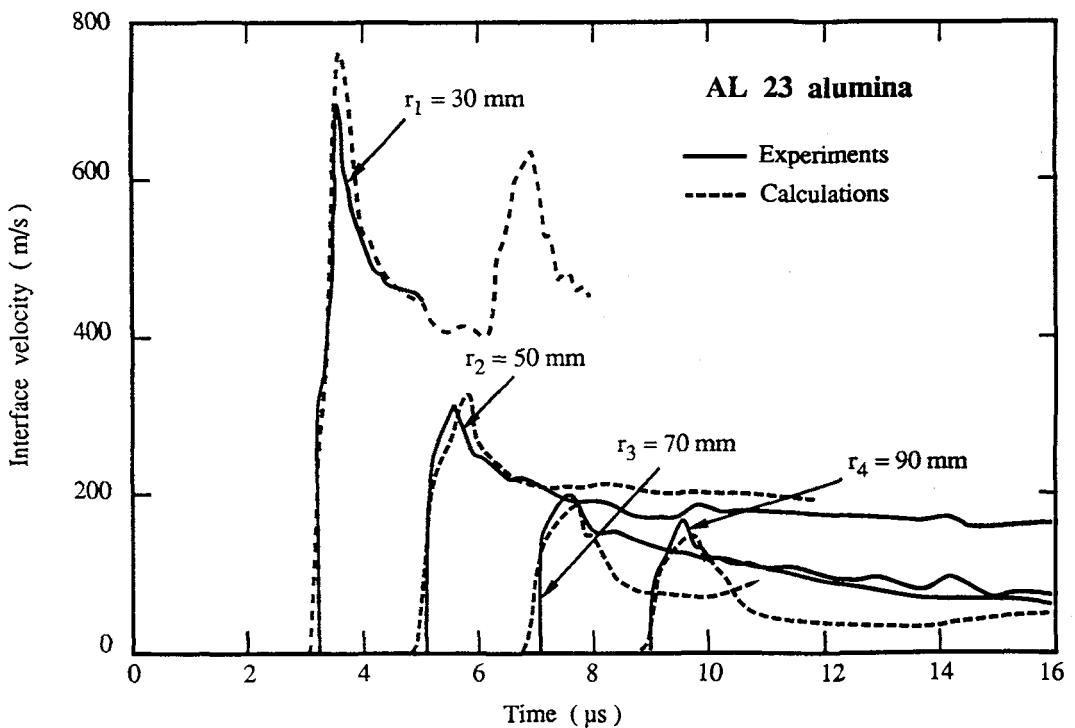


Figure 4 : Comparisons between experiments and monidimensional numerical calculations.

## 6. CONCLUSIONS

In explosive tests, only a few data are available. Some of macroscopic measurements (velocity or stress profiles) can be recorded at given points in particular directions of the specimen and post-mortem observations of the final state of damage can be done. The proposed iterative method permits to optimize this data set and can be a convenient tool to understand the effect of damages on the macroscopic mechanical response of the material. The first results obtained with simplified descriptions and evolutions of the damage are promising. However, many efforts have to be made to improve the description of the damage state and its evolution.

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