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Dynamic fragmentation of an alumina ceramic subjected to shockless spalling: An experimental and numerical study

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A B S T R A C T

Ceramic materials are commonly used as protective materials for infantry soldiers and military vehicles. However, during impact, intense fragmentation of the ceramic material is observed. This fragmentation process has to be correctly numerically simulated if one wants to accurately model the dynamic behaviour of the ceramic material during impact. In this work, shockless spalling tests were performed on an alumina ceramic using the high-pulsed power generator (GEPI) equipment. These spalling tests allowed us to master the experimental strain-rate magnitude of the tensile loading applied to the specimen. The spall strength is observed to be rate dependant and the experimental configuration allowed for recovering damaged but unbroken specimen which gives further insights about the fragmentation process initiated in this ceramic material. The collected experimental data has been compared with corresponding numerical simulations conducted with the DFH (Denoual–Forquin–Hild) anisotropic damage model. This modelling approach relies on the description of the main basic micromechanisms activated at high loading rates using physical parameters related to the population of defects that produces multiple cracking in the ceramic material at high strain-rates. Very good agreement was observed between numerical simulations and experimental data in terms of free-surface velocity, size and location of the damaged zones along with crack density in these damaged zones.

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1. Introduction

Since the 60s, ceramic materials have been considered to be very interesting materials for use as protective armour systems for infantry soldiers, vehicles, and helicopter seats (Barron et al., 1969). Due to their high hardnesses and compressive strengths (reaching several GPas in the case of alumina (Grady, 1998; Gust and Royce, 1971; Rosenberg et al., 1985) or more than 10 GPa in the case of silicon carbides (Bourne et al., 1997; Feng et al., 1998; Forquin et al., 2003a; Vogler et al., 2006)), shattering (Madhu et al., 2005) or erosion of a striking projectile (den Reijer, 1991) is observed during impact. Furthermore, due to their low density, the use of ceramic materials provides an important weight benefit in comparison with monolithic steel plate armours providing the same ballistic efficiency (Roberson, 1995). However, ceramics also exhibit relatively low tensile strengths (compared to their compressive strengths) along with brittle behaviour under both tensile and unconfined compression loading (Forquin et al., 2003a). Thus, an inevitable fragmentation of the ceramic material will

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occur when a projectile hits a ceramic based armour material (Forquin et al., 2003b; Riou et al., 1998; Zinszner et al., 2015). That is why ceramic plates are always backed by ductile plates constructed from metallic materials such as aluminium or composite materials (Medvedovski, 2010). Consequently, the tensile behaviour of the ceramic material along with the fragmentation process play an important role in the behaviour of a specific armour configuration under impact, and require accurate modelling of this fragmentation process in order to achieve an optimum design for the desired armour configuration.

The fragmentation process of ceramics has been extensively studied by means of flyer plate impact experiments. In a spalling test, the interaction of stress waves is used to generate an intense tensile stress and initiate damage leading to dynamic fracture. Bless et al. (1986) conducted spalling tests on two alumina ceramics with different mean grain sizes: Al-300 (20 μm) and AD-85 (5 μm). Experimental results indicated that the strength is reduced when the shock level gets close to the Hugoniot Elastic Limit (HEL) of the sample being tested. However, for low amplitude shock waves, the spalling stress is nearly constant at 400 MPa for Al-300 and 300 MPa for AD-85. Murray et al. (1998) performed spalling experiments on three different alumina ceramics at shock levels under and above the HEL showing again a decrease of the spall strength near and above the HEL. Moreover, the tensile strength of the ceramic grades characterised by similar mean grain sizes (2–4 μm) but different levels of purity and porosity is clearly influenced by the microstructure of these materials. Similar results have been described by Cagnoux and Longy (1988) for five alumina ceramics and by Bourne (2001) on alumina ceramics with purities ranging from 95% to 99%. Although the influence of the shock magnitude has been extensively investigated, the plate impact technique has not permitted studying the sensitivity of ceramic's tensile strength to the strain-rate. A shockless loading generated by an electromagnetic device may be employed to identify the strain-rate sensitivity of the spall strength of ceramic materials (Erzar and Buzaud, 2012). In addition, a standard plate impact experiment necessitates the use of a projectile sabot and propulsive gas that strongly affects the possibility in recovering the damaged sample after the test in order to conduct post-test analyses. Generally, the sample is reduced to dust and small fragments after these kinds of experiments. This limitation can be also overcome by using a high-pulsed power technology.

For several years, numerical simulations have played an important role in the research world. Combined with the constant evolution of computer performances, it allows the prediction of the behaviour and fracture of a test specimen when subjected to mechanical loading such as impact loading for example. However, the choice of the material model may have an adverse effect on the numerical results if the dynamic behaviour of the material is not well captured by the employed constitutive law. In classical macroscopic models, the behaviour of the ceramic is the same at every integration points and the material is considered as a continuous medium. One of the most popular macroscopic models to simulate the behaviour of ceramics under dynamic loading is the Johnson–Holmquist model. First proposed in 1992 with the so-called JH-1 model (Johnson and Holmquist, 1992), it evolved in two other versions, called JH-2 (Johnson and Holmquist, 1994) and JHB (Johnson et al., 2003). Its phenomenological formulation includes some characteristics of the dynamic behaviour of ceramics like a pressure-dependant strength, a growth of damage with the level of plastic strain and an influence of the damaged state on the strength of the material. The tensile behaviour of ceramics is given by a unique value of the maximum tensile hydrostatic pressure value, which can be obtained by spalling plate impact experiments. However, this value is generally calculated as the mean value obtained from several spalling tests and no strain-rate sensitivity of the spall strength is taken into account. Moreover, the damage value is only based on increments of the plastic deformation and inverse approaches are needed to determine the parameters of the damage model. Another model for the shock response of ceramics is given by Rajendran and Grove (Rajendran, 1994; Rajendran and Grove, 1996). In their model, damage evolution is based on the growth of microcracks initiated at flaws initially distributed in the material. Despite the physical description of the damage, the numerical parameters have to be determined using an inverse approach as in the case of the Johnson–Holmquist model. Several other damage models are also based on an initial population of defects in the material such as those used by Hazell and Iremonger (1997), Paliwal and Ramesh (2008), and Keita et al. (2014). However, this last model needs a non-zero initial damage value and an inverse approach is still necessary. Fernández-Fdz et al. (2011) have developed a phenomenological model where the tensile damage is based on the maximum principal stress and a parameter related to the growth rate of the cracks. Despite the ability of existing models to simulate the dynamic behaviour of ceramics, inverse approaches are often required, and reduces their predictive capabilities. The Denoual–Forquin–Hild (DFH) anisotropic damage model (Denoual and Hild, 2000; Forquin and Hild, 2010) aims to alleviate this situation due to the fact that it relies on a description of the main mechanisms activated at the microscale and employs parameters that can be identified from independent experiments.

In this work, an experimental technique based on high-pulsed power technologies is employed to conduct spalling experiments at different strain-rates on an alumina ceramic. In the second section, the alumina ceramic used in this work is described as well as quasi-static ring-on-ring bending tests performed on this alumina ceramic. Next, the spalling tests conducted with the GEPI generator allowed us to perform shockless spalling tests. These tests are detailed with a particular focus on the strain-rate sensitivity of the dynamic tensile strength. In the last section, the Denoual–Forquin–Hild (DFH) anisotropic damage model is presented. Predictions from the modelling of the spalling tests are given in terms of both closed form solution along with numerical simulations. Finally, comparisons are provided between the experimental and numerical results in terms of free surface velocity signal graphs and damage patterns.

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