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Transient stress and failure analysis of impact experiments with ceramics

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ABSTRACT

At Ernst-Mach-Institut (EMI), ductile and brittle materials are studied both experimentally and numerically with the focus on shock and impact loading and associated damage effects. Experimental investigations using plate impact, edge-on impact, penetration and perforation on light gas accelerators provide input for numerical studies and allow verification of constitutive models. Hydrocodes are the standard numerical tool for the simulation of transient processes and basis of the modelling in the present paper. Besides use of commercial codes with mesh-based Lagrangean and Eulerian spatial discretization, an own meshfree SPH code has been developed at EMI. Edge-on impact experiments, plate impact tests and deep penetration in confined targets are simulated to study different loading histories and failure conditions. Significantly different material models based on continuum damage approaches as well as microstatistical modelling of inhomogeneities have been implemented. Their performances in reproducing damage fracture patterns and continued fragment loading in different ceramic types are analysed and compared to edge-on impact experiments.

1. Introduction

1.1. Impact applications and characterization experiments

Ceramics are known to increase the effectiveness of armour at low specific weight. The hardness breaks and starts erosion of the projectile early in the penetration process. However, tensile strength and plastic flow capabilities are generally poor. Efficient application therefore demands coupling with a deformable backing structure absorbing high amounts of energy while supporting the fractured ceramic. Fig. 1 (left) illustrates the section of a recovered ceramic plate with steel backing during an impact of moderate energy (Riou [1]). The SiC layer broke along conical cracks spreading up the impact momentum on an area wider than the projectile diameter, thereby avoiding plugging failure of the ductile material.

The depth-of-penetration (DOP) test configuration, illustrated in the experimental Fig. 1 (right) and simulation Fig. 7 (left) is widely used to compare the efficiency of ceramics to erode and defeat projectiles or shaped charge jets (e.g. Hohler et al. [2], Rosenberg et al. [3]). A monolithic or layered block of ceramic (light gray in Fig. 1), possibly pre-stressed to increase the effect of interface defeat (Holmquist and Johnson [4]), is combined with a semi-infinite block of armour steel (dark gray). The ultimate penetration depth, here of a tungsten rod, is measured to compare performances of different materials.

Besides these applications involving complex stress states, there are precise high strain rate experiments to derive constitutive parameters of ceramics. Hopkinson–Bar tests can provide stress–strain curves in compression or dynamic tensile strength in spallation configuration. Dynamic states of uniaxial stress are examined with strain rates of the order of $10^3\,s^{-1}$ (e.g. Najar [5]). Strong shock waves and compressive strain rates up to $10^6\,s^{-1}$ are reached in planar plate impact (PPI) experiments. Fig. 2 shows sample configurations used by Winkler [7], Hiltl and Nahme [6] together with VISAR velocity measurements. The right side of the figure displays spall strength σ_{SP} of different ceramics resulting from compression and subsequent release waves in the GPa range. The underlying stress histories are analysed and discussed in more detail in Section 2 and Fig. 6.

As both PPI and DOP tests do not provide detailed information about the onset and propagation of damage, the edge-on impact (EOI) has been developed as additional analysis tool [8]. Fig. 3 shows a schematic of the experiment originally designed by Schardin [9], the founder of Ernst-Mach-Institut, in the late 1930s to investigate fracture in glasses. Nowadays, ceramic plates of 10 cm × 10 cm × 1 cm are impacted on their edge by a cylindrical steel projectile (r = 1.5 cm, l = 2.3 cm) at velocities between 50 and 1000 m s^{-1}. During the impact, a series of 24 photos is taken with a Cranz–Schardin high speed camera at frame rates up to 10 MHz. In order to obtain clear pictures, diffusive reflecting surfaces have to be finished to a low surface roughness and coated by a reflecting layer. With this type of experiment different fracture phenomena

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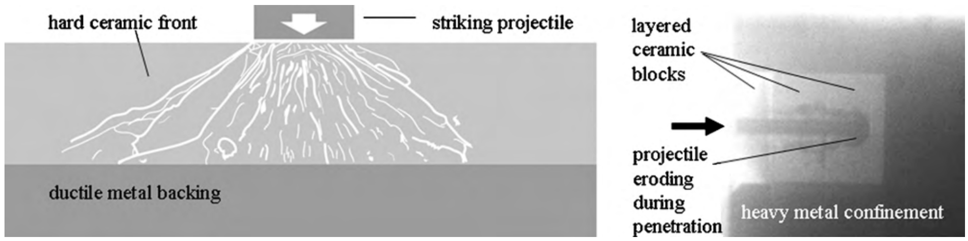

Fig. 1. (Left) Schematic of a hard ceramic front layer in protective design as studied by Riou [1]. (Right) Flash X-ray of an eroding penetrator during a DOP test in layered ceramic target (V. Hohler, EMI).

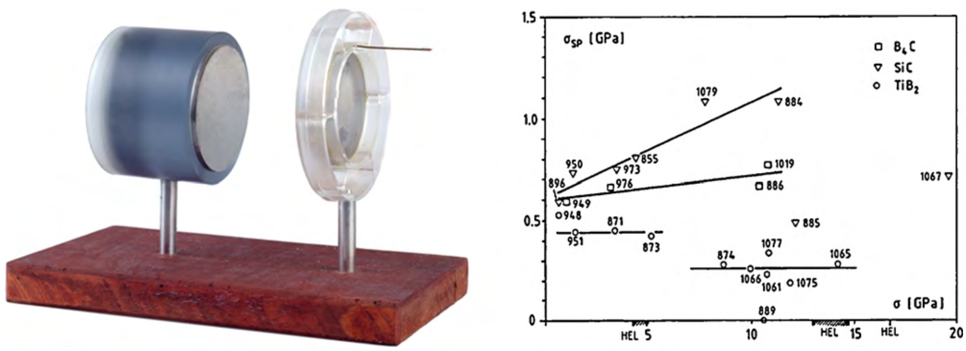

Fig. 2. (Left) Projectile with sabot and target for planar plate impact experiments at highest strain rates. (Right) Spall strength σ_{SP} of different ceramics as function of the incident compressive stress σ resulting from impact velocities between 850 and 1080 m s^{-1} [7].

and patterns can be observed depending on the ceramic material, the state of wave propagation and the impact energy. Analysing the complete picture series of one test allows to deduce crack front velocities v_D as a function of the projectile velocity v_P as shown in Fig. 3 (right). Since the fragments are not further loaded after the cracking process, optical and microstructural analyses of the crack edges can be conducted after the experiment.

1.2. Selected modelling and simulation approaches

EOI experiments have served to calibrate and validate a number of different ceramic modelling approaches. Riou [1,10] and Grujicic et al. [11] used continuum damage approaches in mesh-based Lagrangean hydrocodes. Denoual and Hild [12,13] combined probabilistic and multi-scale strength descriptions with the same governing equations and discretization method. Steinhauser et al. [14] studied a fundamentally different approach: his two-dimensional discrete elements with potentials for repulsion and cohesion require a minimum set of parameters. Failure thresholds for compression and tension release bonds between discrete elements and allow crack propagation, which is compared to crack patterns and velocities of experiments on Al_2O_3 and SiC.

The present paper is using Lagrangean hydrocode simulation approaches [15] with Smooth Particle Hydrodynamics (SPH) descriptions [16,17] in the EMI code SOPHIA. The conservation equations for mass, momentum and energy are solved in their differential non-conservative form:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho\nabla\cdot v_i \tag{1}$$

$$\frac{\mathrm{d}v_i}{\mathrm{d}t} = \frac{1}{\rho_0}\nabla\cdot\sigma_{ij} \tag{2}$$

$$\rho\frac{\mathrm{d}e}{\mathrm{d}t} = \sigma_{ij} : \nabla v_i \tag{3}$$

The basic SPH concept is to approximate the value of any vector function $f(x)$ and its gradients at the location x as an integral over the value of the same function in neighbouring positions x' times an interpolating kernel function $W(x-x', h)$. The value of a function (4) and its derivative (5) at a particle denoted by subscript i is calculated by summing the contributions from a set of neighbouring particles

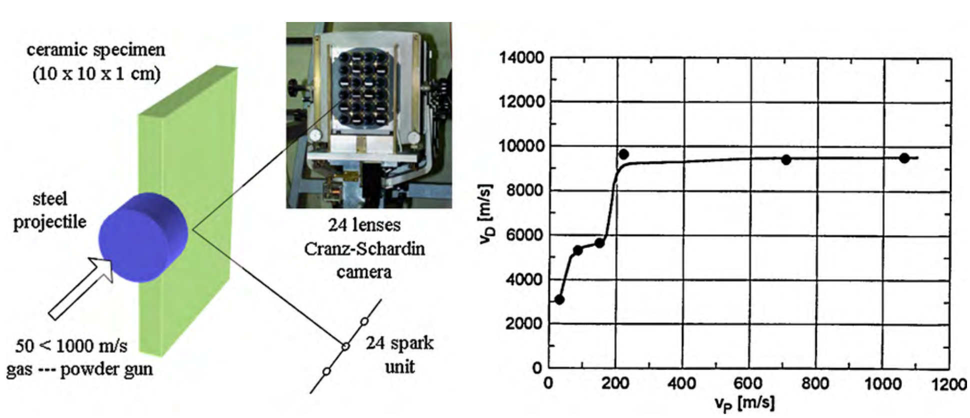

Fig. 3. Edge-on impact experiment (EOI), Cranz–Schardin camera and measured crack velocities [8].