# Comparison of Two Processing Techniques to Characterise the Dynamic Crack Velocity in Armour Ceramic Based on Digital Image Correlation

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**Abstract:** Ceramic materials are being more and more used in bi-layer shielding solutions. When impacted, substantial tensile damage creates within the ceramic tile that manifests as numerous oriented cracks. Understanding the dynamic fracture response under high strain-rates and at the level of a single dynamic crack is of major importance in pushing forward the design of resilient ceramic-based armour solutions. For that purpose, a testing technique called the Rocking-spalling test, using a single Hopkinson bar, is used in this work. This experimental method enables the study of a single quasi-straight dynamic crack which propagates through a double-notched rectangular specimen. A projectile impacts the bar generating a compressive pulse that propagates to the specimen and reflects from its free-end. Upon reflection into a tensile wave, a rocking effect takes place, thanks to the notch positioning, which leads to the inception of a single crack that propagates from the notch tip. The entire crack propagation process is filmed with an ultra-high-speed camera with exposure times down to 200 ns. Digital image correlation (DIC) was used to extract meaningful kinematics at the sample surface. Two post-processing methods for determination of crack velocity in a porous silicon carbide ceramic (Forceram®) are presented.

## 1. Introduction

Depending on the strain-rate $\dot{\varepsilon}$, single fragmentation in quasi-static ($10^{-5}$–$10^{-1}$ $s^{-1}$) or multiple fragmentation in dynamic (> $10^{1}$ $s^{-1}$) takes place. Figure 1a on toughed alumina ($Al_2O_3$) and Figure 1b on silicon carbide (SiC) ceramics illustrate respectively the two regimes of failure. One way to explain the single-multiple transition point is the use of Monte-Carlo simulations [1] of a cubic volume loaded with a randomly-located set of flaws density, as illustrated in Figure 1c for a dense SiC.
The Denoual-Forquin-Hild (DFH) model [2,3] is a micro-mechanical anisotropic tensile damage model based on the crack inception from critical defects activated upon random tensile stress loading (described with a population following the Weibull's law [4,5]) and the obscuration (or relaxation) phenomenon that captures well this transition and that is suitable for modelling the fragmentation in various brittle materials. One of the key parameters within the model is the crack propagation velocity, described by equation (**1**) [2,3].

$$V_0.(T-t) = S.[v_{crack}.(T-t)]^n \tag{1}$$

One of the parameters, $v_{crack}$, corresponds to the terminal velocity at which crack propagates at "maximum speed". Consequently, reliable experimental measurement of crack velocity and its characterisation are of crucial importance for improving the accuracy of the numerical simulation of impact events. The theoretical crack speed is often provided either as a function of the elastic 1D-longitudinal (or irrotational) wave velocity $C_0$ in a bounded medium, which is the speed of the fastest elastic wave that can propagate in solids, or as a function of surface (or Rayleigh) wave speed $C_R$ in solids, which carries most of

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the energy throughout a shock [6,7]. According to Broek (1984) [8], the crack velocity accelerates to an asymptotical limit of $kC_0$ ($k$ being a constant equal to 0.38 based on energetic consideration). Yoffé (1951) [9] indicated that a crack tends to branch out or to become curved when travelling faster and faster because there is enough energy to drive two cracks independently. Ravi-Chandar and Knauss (1984) [10] stated that branching may occur for even lower velocities than predicted by Yoffé (1951) [9].

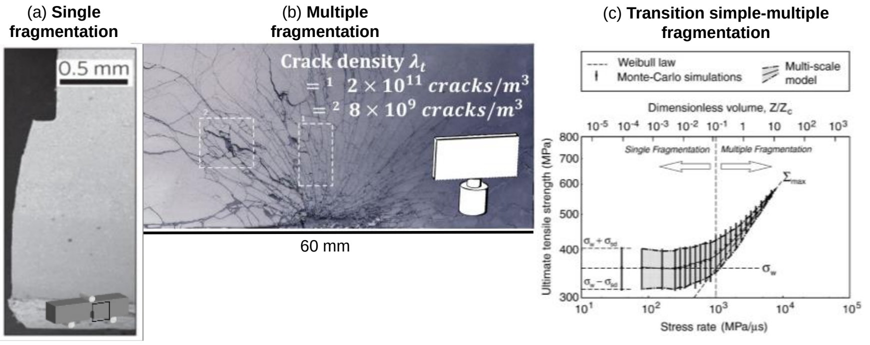


**Figure 1: Examples of: (a) single and (b) multiple fragmentation tests, with (c) the transition between single and multiple fragmentations (adapted from [11], [12] and [1]).**

Experimental works on brittle materials showed that the limiting velocity regarding the Rayleigh wave speed $C_R$ is material dependant: $0.45C_R$ in Homalite-100 (polyester resin) [10], $0.50C_R$ [14] or $0.60C_R$ [15] in glass, between $0.53C_R$ and $0.57C_R$ in concrete (R30A7) [16], $0.60C_R$ in Plexiglas (Polymethyl methacrylate (PMMA) brittle thermoplastic) [17]. Recently, Anderson Jr., Bigger and Weiss (2014) [18] performed ballistic impacts on borosilicate glass ceramics using a high-speed video camera with interframe time ~ 5 µs. They observed crack speeds around 1.92 km/s (~ $0.59C_R$[1]) independent from the impact velocity, confirming that crack velocity is an actual material property. However, the effects of the material microstructure were not discussed. Besides, other parameters could influence the crack velocity: when the loading is applied directly at the crack tip [19], presence of void [10,20], change of material behaviour ahead of the crack tip with particular microstructures (increase in fracture toughness $K_I$ known as the R-curve effect). Under dynamic loading, some main challenges are owing to a large number of micro-cracks generated under impulsive loading which makes the isolated visualisation difficult (crack monitoring) as well as the interpretation of the results due to multiple crack interactions. This leads to a clear need for an experimental method that is able to generate a single dynamic crack under high strain-rate loading.

The current paper presents one such experimental method in conjunction with Digital Image Correlation (DIC) to obtain a crack speed during single fragmentation but in dynamic. The crack tip speed cannot be directly measured by simply looking at the images since the crack opening displacement is far beyond pixel size (1 to 3 µm). Comparing the first image and last image of the sequence only provides an idea on the crack path; however, the crack kinematics stays out of reach. In this situation, a sophisticated extraction method based on image correlation serves as one of the only method of obtaining such information.
For this reason, two image processing methods are used on a series of ultra-high-speed images obtained with 0.2 µs exposure as to extract the crack velocity of porous Sain-Gobain's armour SiC ceramic commercially named Forceram [21]. The acquisition sequences are obtained by filming a surface of a rectangular sample while being dynamically loaded through the experimental technique called the Rocking by spalling (or "Rockspall") test [16,22]. A single quasi-straight dynamic crack is generated which propagates through a 60×30×7-mm double-notched specimen at high strain-rate. This technique was already employed in [16,22] on concrete material in which the information obtained from DIC was compared to the data of a single velocity-gauge glued on the sample which allowed the evaluation of the crack velocity.

[1] $C_R$ was calculated using material properties of Borofloat 33 found in [13] ($C_R \sim 3238\ m/s$).