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Influence of confining prestress on the transition from interface defeat to penetration in ceramic targets

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Abstract

Replica scaled impact experiments with unconfined ceramic targets have shown that the transition velocity, i.e., the impact velocity at which interface defeat ceases and ceramic penetration occurs, decreased as the length scale increased. A possible explanation of how this scale effect is related to the formation of a cone crack in the ceramic has been presented by the authors in an earlier paper. Here, the influence of confinement and prestress on cone cracking and transition velocity is investigated. The hypothesis is that prestress will suppress the formation and growth of the cone crack by lowering the driving stress. A set of impact experiments has been performed in which the transition velocity for four different levels of prestress has been determined. The transition velocities as a function of the level of confining prestress is compared to an analytical model for the influence of prestress on the formation and extension of the cone crack in the ceramic material. Both experiments and model indicate that prestress has a strong influence on the transition from interface defeat to penetration, although the model underestimates the influence of prestress.

Keywords: Impact; Ceramic; Armour; Interface defeat; Dwell; Confinement; Prestress

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1. Introduction

The high strength of armour ceramics [1–3] makes it possible to partially or totally defeat high velocity projectiles directly at the surface of the ceramic material. This phenomenon is called interface defeat or dwell [4–17] and is an important defeat mechanism in, e.g., light armour applications.

One limitation when applying this in heavier armour designs is that it appears to be length scale dependent. Replica scaled impact experiments with unconfined ceramic targets show that the transition velocity, i.e., the velocity at which interface defeat ceased and ceramic penetration occurred, decreased as the length scale increased [11]. A probable explanation of the observed scale effect is that although maximum shear strength determines the upper bound for the transition from interface defeat to penetration, it is usually limited by the formation and growth of macroscopic cracks. Since the crack resistance of ceramic materials decreases with increasing length scale, in contrast to the otherwise scale-invariant stress field, the extension of a crack to a critical size will occur at a lower impact velocity in a larger target. An analytical model in [11] for the influence of length scale on the growth of a cone shaped modus I crack in thick unconfined ceramic targets gave reasonable results compared to the replica scaled impact experiments. The model showed that the projectile pressure at transition, i.e., the impact velocity at which the contact pressure exceeds the strength of the ceramic material and penetration initiates, is proportional to one over the square root of the length scale.

A possible way to suppress the formation and growth of macroscopic cracks is to prestress the ceramic material. The influence of prestress and the related failure modes of impacted ceramics have been studied by several authors. The papers [18–20] report experimental data on small calibre projectiles impacting thin prestressed ceramics (i.e., the thickness is of the same order as the diameter of the projectile). These studies show that prestress reduces damage in the form of fewer macroscopic cracks and that the trajectory of possible cone cracks becomes shallower. An increase in protective performance was also observed. The papers [8,9] report experimental data on model scale long rod projectiles impacting thick ceramic targets (i.e., the thickness is much larger than the diameter of the projectile). The experiments in [8] with large and heavily confined and prestressed targets showed similar interface defeat velocities as small, unconfined targets in [9]. This indicates the need of prestress in larger targets.

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Holmquist and Johnson [21] and later Runqiang et al. [22] conducted a computational study on the responses of a small scale thick prestressed ceramic target tested by Lundberg et al. [7]. Various levels of prestress and stress states were simulated. Their studies showed that prestress enhanced the performance and that the velocity at which ceramic penetration occurred, i.e., the transition velocity, could be increased by prestress.

This paper explores the influence of a radial confining prestress on the transition from interface defeat to penetration for a thick ceramic target. Although the physical background of the influence of prestress on the transition velocity in ceramic targets is not fully explained, impact experiments as well as modelling indicate that it is intimately linked to ceramic fracture. A hypothesis proposed in [11] is that the centre part of the ceramic suddenly loses radial support as a result of the cone cracking. A confining prestress will suppress the growth of the cone crack by lowering the stress intensity over the crack tip. In order to overcome this virtual toughening of the ceramic, the projectile pressure on the surface of the target must be increased relative to that for an unconfined target in order to initiate critical fracture. A set of impact experiments have been performed in which the transition velocities for four different levels of prestress were determined. Two grades of silicon carbide ceramics with slightly different mechanical properties were used. The experimental technique used is presented in the paper together with the determined transition velocities versus radial confining prestress. The experimental data are compared to an extended version of the model presented in [11].

2. Model of cone crack under confining prestress

The influence of a radial confining prestress on the formation and extension of a cone shaped crack to a critical size is approximated in the model by the assumption that the crack extension occurs along a surface of principal stress. The normal stress on this surface is calculated for the case of an axi-symmetric contact pressure from a projectile in a state of interface defeat and for a radial confining prestress, respectively. The critical normal stress for propagating the crack is determined through: (i) a stress intensity factor at the tip of the crack and (ii) a function of the influence of external load and geometry on the path of the crack.

The detailed description of the present model is divided into four sections: 2.1 Projectile contact pressure and stresses in the target, 2.2 Principal surfaces and stresses, 2.3 Crack initiation and propagation under confining prestress and 2.4 Crack opening under confining prestress.

2.1. Projectile contact pressure and stresses in the target

A long cylindrical projectile is assumed to flow axi-symmetrically on the flat and friction-free surface of an otherwise unbounded, but radially prestressed target, see Fig. 1. The flow and the loading on the surface are steady, i.e., the initial transient part of the impact process is not considered. The target material is linearly elastic with Young's modulus E and Poisson's ratio ν, respectively. The material of the projectile is linearly elastic and perfectly plastic with bulk modulus K_p, yield strength σ_{yp} and density ρ_p.

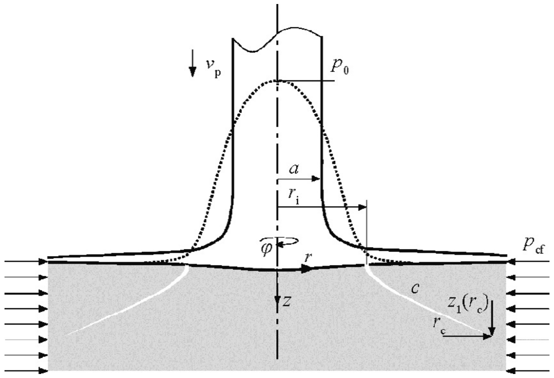

Fig. 1. Projectile shape (solid line), axi-symmetric pressure of projectile (dotted line) and crack trajectory in target (gray) during a state of interface defeat.

With the assumption that the effects of yield strength and compressibility are small relative to that of inertia, the axi-symmetric contact pressure of projectile load can be approximated [7] by

$$p(r,\alpha,\beta) \cong q(r)\left(1+\frac{1}{2\alpha}+3.0\beta-1.6\beta^2\right) \tag{1}$$

where $q(r)$ is the radial pressure distribution corresponding to inertia,

$$\alpha=\frac{K_p}{q_p}, \quad \beta=\frac{\sigma_{yp}}{q_p} \tag{2}$$

and

$$p_0=p(0,\alpha,\beta), \quad q_p=q(0)=\frac{1}{2}\rho_p v_0^2 \tag{3}$$

Here v_0 is the impact velocity of the projectile and q_p is the stagnation pressure of an ideal fluid with density ρ_p. The dimensionless parameters $\alpha >> 1$ and $\beta << 1$ relate elastic and plastic effects to the effect of inertia. The influence of β in Eq. (1) is evaluated from simulations in [17] and the radial distribution of $q(r)$ is taken from a low-velocity water jet [7].

The stress field $\sigma_{ij}(r,z)$ of projectile pressure p in the semi-infinite elastic target half-space, is expressed by a Boussinesq's potential as

$$\sigma_{ij}(r,z)=\int_0^{2\pi}\int_0^{A} I_{ij}(r,z,\upsilon,\varsigma)\,p\varsigma \mathrm{d}\varsigma \mathrm{d}\upsilon \tag{4}$$

where I_{ij} is an influence-function (negative in compression) for a point load of the amount of $p\varsigma d\varsigma d\upsilon$ at a surface point (υ,ς), with p according to Eq. (1). Indices i, j are the generic spatial variables r, φ, and z and A is the radius ς of the circular limit of the distribution of projectile pressure. The radial stress component σ_{rr} is affected by the confining prestress p_{cf} so that the stress components from projectile and confinement together are expressed as

$$\begin{aligned}&\sigma_{ij}(r,z)\rightarrow\sigma_{ij}(r,z), \quad ij\neq rr,\\&\sigma_{rr}(r,z)\rightarrow\sigma_{rr}(r,z)-p_{cf}, \quad 0\leq r, \quad 0\leq z, \quad 0\leq p_{cf}.\end{aligned} \tag{5}$$