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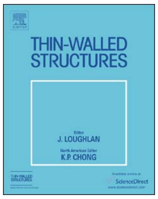

Full length article

Criterion for interface defeat to penetration transition of long rod projectile impact on ceramic armor

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ABSTRACT

In this paper, an analytical model for the prediction of damage evolution, through impact of long rod projectile (LRP), at interface defeat condition, against silicon carbide (SiC) target is developed. The model comprises four calculation parts, namely interface pressure distribution, stress state in the ceramic target, wing cracks micro-mechanical and macro-cone crack propagation. A micro-mechanical constitutive model with wing crack distribution is used for inelastic deformation of ceramic. Subsurface damage evolution in ceramic impacted by blunt and conical LRPs at different impact velocities and length scales are presented to depict the potential mechanisms involved in transition from interface defeat to penetration. The damage evolution results agree well with the available literature experimental measurements. The proposed possible criteria can be used to predict the interface defeat to penetration transition for blunt and conical LRPs.

1. Introduction

Ceramics are widely used in armor systems in fighting vehicles and tanks because of low density, high compressive strength and hardness [1]. The high hardness of ceramics helps in retarding the projectiles power by plastically deforming them. Further, ceramics may force the high velocity projectile to flow radially with no significant penetration, a phenomenon called *dwell* or *interface defeat* [2]. In the literature, dwell is referred to radial flow of the projectile on the surface of the target for some time (dwell time) followed by penetration into the ceramic while if no penetration occurs the phenomenon is termed as interface defeat. Interface defeat or dwell are very important mechanisms to enhance armor ballistic performance during which the kinetic energy of the projectile is largely reduced without considerable penetration in ceramic armor [2]. The interface defeat phenomenon was first described by Wilkins [3] and further investigated by Hauver et al. [4–7]. Since then, considerable experimental, theoretical and simulation studies regarding dwell or interface defeat phenomena have been performed. These results show that the interface defeat phenomenon is controlled by dynamic behavior of ceramic, constrained state, geometric and material properties of the projectile and impact conditions. The damage evolution of ceramics subjected to high-velocity impact is a key factor influencing the transition from interface defeat to penetration. Hauver et al. [7] presented the damage results of heavy confined SiC impacted by long rod projectile (LRP) at interface defeat condition showing subsurface comminuted damage zone and cone cracks emanating from the impact surface. LaSalvia et al. [8,9] carried out dynamic indentation experiment to investigate the damage evolution in silicon carbide (SiC) impact by tungsten carbide (WC) sphere at different velocities. Limited analytical models have been proposed for the damage evolution of ceramic under impact loading. LaSalvia et al. [10] used a wing-crack model to predict compressive failure in ceramic and derived the stress field equations only on the axis of symmetry of the ceramic target. Lundberg et al. [11,12] proposed a simplified model for incipient cone crack propagation. They assumed that the contact pressure radius does not change with projectile velocity through the time. Anderson et al. [13] presented an analytical model that captures the essential mechanics of dwell and interface defeat based on Alekseevskii-Tate model [14,15]. Li et al. [16] extended the Alekseevskii-Tate model [14,15] to describe the velocity decay and mass loss of flat-end and conical-end LRP. Grace [17] presented an analysis of interface defeat to include loading histories during impact, calculation of stress states and correlation to damage within the ceramic material. Iyer [18] proposed a relationship between multi-axial stress state and internal fracture patterns in sphere-impacted SiC and calculated the macro-crack evolution based on Hertzian contact theory. Li et al. [19] summarized three deformation modes for LRP impact onto ceramics, namely interface defeat, transition from interface defeat to penetration and normal penetration. They discussed the critical transition time based on the damage and failure of ceramic. For dynamic constitutive

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Abbreviations: DOP, depth of penetration; LRP, long rod projectile

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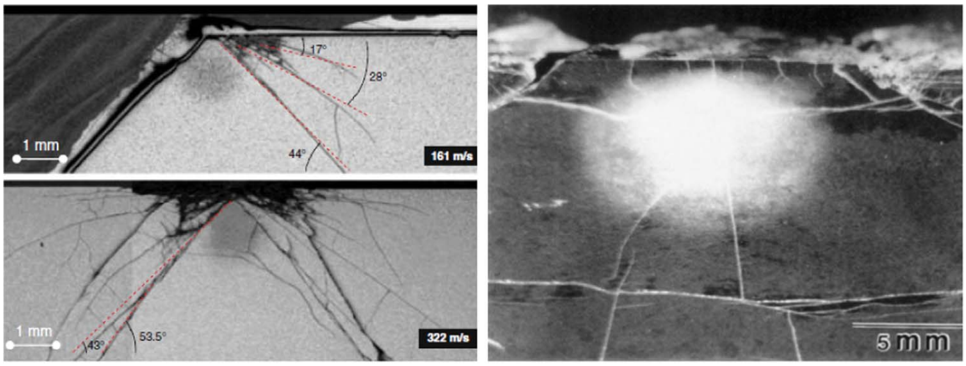
Nomenclature

a	initial flaw size
c	cone crack length
c_c	critical cone crack length
$\dot{c}$	cone crack growth rate
C_R	Rayleigh wave speed
D	current damage state
D_0	initial damage state
E	Young's modulus
F	load
f	volumetric flaw density
K_p	bulk modulus of LRP
K_I	mode I stress intensity
K_{IC}	mode I fracture toughness
l	eroded length of LRP
l_r	residual length of LRP
l_1	cone length of conical-end LRP
l_2	shank length of conical-end LRP
$l_{0,f}$	initial length of flat-end LRP
$l_{0,c}$	initial length of conical-end LRP
l_c	cone crack propagation length
l_{wc}	length of wing crack
P_d	depth of penetration
$p(r)$	contact pressure distribution
p_0	peak contact pressure
q_p	stagnation pressure
r_1	tip radius of conical-end LRP
R	general contact radius
R_0	radius of LRP in cylindrical part
R_c	pressure distribution contact radius
R_{cr}	LRP critical radius
R_t	penetration resistance of ceramic
t	time
U	penetration velocity
V	projectile velocity (tail velocity)
V_0	initial impact velocity of LRP
V_{cr}	LRP critical impact velocity
V_f	velocity of bounced back eroded LRP
V_t	transition velocity
Y_p	yield stress of LRP material
ρ_p	density of LRP
ρ_t	density of ceramic
σ_0	quasi-static strength of ceramic
σ_m	mean stress in the target
σ_e	effective (von-Mises) stress
σ_1	maximum principal stress
σ_c	critical stress
z, r, θ	cylindrical coordinate in the target
$\sigma_{rr}, \sigma_{\theta\theta}, \sigma_{zz}, \tau_{rz}$	stress in target in cylindrical coordinate
α	crack orientation factor
β	parameter to ensure 2D compatibility
γ	crack geometry factor
μ	friction coefficient
ν	Poisson's ratio of ceramic
η	parameter related to LRP flow angle
λ	stress triaxiality
ψ	wing-crack angle
θ_0	cone tip angle
θ_f	flow angle of eroded LRP material
θ_c	angle of crack with target surface
$\omega(l_c)$	weight function

models of ceramics, phenomenological damage mechanics and micromechanically motivated models are most common ways which characterize the response of ceramics to impact loading. Among the phenomenological models, JH model, proposed by Johnson and Holmquist [20–23], is the most complete one considering Drucker-Prager yield surface and damage based on effective plastic strain. The JH model has multiple constants that require calibration through dynamic measurements of materials. Micromechanically motivated models incorporate aspects of the physics governing compressive damage and plastic deformation. Deshpande and Evans [24,25] devised a micromechanical model (DE model) based on two specific inelastic phenomena, namely lattice plasticity and micro-cracks evolution from pre-existing flaws. Wei et al. [26,27], Gamble et al. [28], Compton et al. [29,30] and Holland and McMeeking [31] extended the DE model to investigate the relationship between the mechanical and microstructural properties of ceramics and their rate-dependent fracture strengths in uniaxial compression.

During shock load compression or intense dynamic loading, ceramic experiences inelastic deformation resulting in subsurface damage and cone crack evolution. If the impact loading is not large enough to induce plastic deformation and flow in ceramic material, the LRP front will flow laterally on the ceramic surface while the LRP tail motion continues. With the increase in impact loading, the subsurface damage and cone crack are expected to increase in size which finally results in LRP penetration into the ceramic. In other words, interface defeat to penetration transition is controlled by damage evolution in the ceramic. To analyze the dynamic response of ceramic target impacted by LRP, a model consisting of four calculation parts, namely interface pressure distribution, target stress state, wing cracks micro-mechanical model and macro-cone crack propagation, is developed to describe the damage evolution of ceramic under interface defeat. The stress field distributions on the ceramic surface, the axis of symmetry and also on a



(a) (b)

Fig. 1. Typical damage results of SiC impacted by (a) WC sphere at two impact velocities from the work of LaSalvia et al. [10] and (b) tungsten LRP from the work of Hauver et al. [7].