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Thermal-mechanical analysis on the mass loss of high-speed projectiles penetrating concrete targets

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ABSTRACT

The significant mass loss of the kinetic energy (KE) projectile has been observed in the high-speed penetration (usually $v_0 > 1$ km/s) into concrete target, resulting in nose abrasion, bending, and trajectory deviation as well as great drop of the Depth of Penetration (DOP). The thermoplastic failure of material peeling from the thin exterior interface between the projectile and the concrete is the main mechanism of the mass loss. Combining the heat generated from the friction work and the plastic deformation work during the high-speed penetration process, a discrete iterative method is proposed to investigate the movement and the nose shape variation on the basis of thermoplastic instability of the material. Utilizing the temperature-based failure criterion and the Johnson-Cook (J-C) constitutive model, the receding displacements of the discrete points are determined by the gradient distribution of the temperature change along the depth from the surface of a projectile, which result in blunting of the projectile nose. The predictions of the nose shape, the percentage of the mass loss and the DOP were validated against the experimental data. Then further studies are conducted to investigate the critical velocity of mass loss and the "secondary peak" deceleration. The onset of the mass loss and the occurrence of the distinct pulse of the deceleration in the tunnel stage are regarded as the symbol of the lower and upper velocity limits of the nondeformable penetration regime. In addition, through the comparison of the percentages of heat generated with different mechanisms at different locations of the projectile, the dominant mechanism of the mass loss between the friction and plastic deformation is analyzed to get an insight into the high-speed penetration process.

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1. Introduction

Deep penetration of the high-speed kinetic energy (KE) projectile into concrete target has intrigued the weapon designers due to the rapid development of constructions of both ground and underground military fortifications protected by reinforced concrete. The theoretical models published previously (Rosenberg and Dekel, 2009; Tate, 1967; Kennedy, 1976; Li and Chen, 2003) were mainly based on the hypothesis of "rigid" projectile in the low-speed penetration range ($v_0 < 1$ km/s), ignoring the influence of mass abrasion occurred at the projectile. However, with increasing the impact velocity (1 km/s $< v_0 <$ 2 km/s), the earth penetration weapon (EPW) may face the problem of structural integrity caused by the serious mass loss. The related phenomena, such as nose abrasion, bending or breaking of the projectile, were observed in many penetration experiments (Alekseevskii, 1966; Forrestal et al., 1996; LundgrenHigh-velocit, 1994; Frew et al., 1998), resulting in the trajectory deviation as well as dramatic drop of Depth of Penetration (DOP). Studying mechanisms of the mass loss of a projectile during high-speed penetration has been a topic of interest in the international research community, especially in the weapon development and engineering protection field.

The systematic experimental research on penetration experiments into concrete and grout targets was conducted by Forrestal et al. (1996) and Frew et al. (1998,2000,2006), which produce the most authoritative experimental data. Mass loss up to 7% of the original projectile was recorded when the striking velocity exceeds 1200 m/s, resulting in a dramatic decline of the DOP. Similar experimental investigation was undertaken by He et al. (2010a) and Yang et al. (2012a), which mainly focused on the transition from

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Nomenclature

Parameter	Units	Parameter in Johnson-Cook model
A	MPa	Instant deceleration of projectile
a	m/s^2	Parameter in Johnson-Cook model
B	MPa	Instant length of projectile nose
b	m	Initial length of projectile nose
b_0	m	Parameter in Johnson-Cook model
C		Heat capacity of projectile
c_p	J/(kg·K)	Heat capacity of concrete
c_c	J/(kg·K)	Diameter of projectile
d	m	Resistance force on the nose of projectile along the *X* axis
F_x	N	Unconfined compressive strength of concrete
f_c	MPa	Frictional force on projectile
f	MPa	Shear modulus
G	GPa	Thermal conductivity of projectile
k_p	W/(m·K)	Thermal conductivity of concrete
k_c	W/(m·K)	Dimensionless factor for the depth of crater stage
k'		Constant parameter in Eq. (11)
k_1	MPa·s/m	Constant parameter in Eq. (11)
k_2		Length of projectile
L_p	m	Width of the each discrete stick
l_c	m	Instant mass of projectile
M	kg	Initial mass of projectile
M_0	kg	Parameter in Johnson-Cook model
m		Parameter in Johnson-Cook model
n		Discrete number of the HAZ
n_{xHAZ}		Discrete number of each time step Δt.
n_{tHAZ}		Total discrete number of penetration time
ni		Total discrete number along the radius
nj		Nose factor in Eq. (1)
N		Normal pressure on projectile
p	MPa	Constant parameter in Eq. (13)
p^*		Heat generation by friction
Q	J	Heat generation by friction conducted into projectile
Q_p	J	Heat generation by friction conducted into concrete
Q_c	J	Dynamic strength parameter of concrete

(*continued*)

R_c	MPa	Radius of projectile
r	m	Dimensionless constant
S		Initial temperature
T_0	K	Critical temperature
T_{cr}	K	Parameter in Eq. (18)
T_{DRX}	K	Melting temperature
T_m	K	Temperature distribution generated by friction
T_t	K	Temperature distribution generated by plastic work converted to heat
T_a	K	Total temperature distribution
T_{total}	K	Instant velocity of projectile
v	m/s	Critical velocity for mass loss
v_s	m/s	Initial velocity of projectile
v_0	m/s	Instant tangential velocity of projectile in Fig. 2
v_τ	m/s	Instant normal velocity of projectile in Fig. 2
v_n	m/s	The width of the HAZ
w_{HAZ}	μm	The width of the ASB
w_{ASB}	μm	Depth of the crater stage
Z_1	m	Instant depth of penetration
z	m	Constant parameter in Eq. (11)
α		Plastic work to heat conversion factor.
β		The percentage of mass loss
γ		The angle in Fig. 2
φ		$\theta=\pi/2-\varphi$
θ		CRH (caliber-radius-head) for ogival nose
Ψ		The effective strain rate at the contact shear plane *AB*
$\dot{\bar{\varepsilon}}_{AB}$	s^{-1}	The effective strain at the contact shear plane *AB*
$\bar{\varepsilon}_{AB}$		Parameter in Eq. (18)
$\dot{\varepsilon}_{DRX}$	s^{-1}	Coefficient of friction
μ		Density of projectile material
ρ_p	kg/m^3	Density of concrete
ρ_c	kg/m^3	
Superscript		Number of time steps
i		
Subscript		Sequence number in spatial dimension
j		Parameter in Johnson-Cook model

rigid to deformable penetration state with various strengths of the projectiles. It was shown that the curved trajectory, erosion and bending of projectiles are the common phenomena in the high-speed penetration. Furthermore, Silling et al (Silling and Forreatal, 2007). established a linearly proportional relationship, through empirical fitting of the experimental data, between the mass abrasion and the initial kinetic energy of a projectile below the velocity of 1000 m/s. Meanwhile, Chen et al. (2010) summarized the experimental data (Forrestal et al., 1996; Frew et al., 1998) and pointed out that the mass loss is closely related to the striking velocity of the penetrator and the category of the aggregate casted in the concrete target. Obviously, figuring out the influence of heat generated by dynamic friction between the projectile and targets is essential for understanding the thermo-mechanical mass loss process of a projectile. Klepaczko and Hughes (2005) conducted a theoretical investigation into the surface layer thermodynamics of steel projectile and proposed universal parameters, such as the rate of wear and rate sensitivity of wear. Recently, Guo et al. (2014) undertook a systematic investigation on the surface evolution of the recovered projectile subjected to a high-speed penetration at the microscopic scale. Microstructural features, including the mixed zone (MZ), the refined zone (RZ) and original zone (OZ), were analyzed respectively. In addition, the underlying mechanisms of the mass loss during high-speed penetration were demonstrated.

Due to the complex transient characteristics of the high-speed penetration process, it is very difficult to record the real-time physical parameters in experiments. Relevant theoretical research is necessary to reveal the underlying mechanisms of the mass loss. Based on the assumption that the heat converted from friction work melt the material on the nose of the projectile, an approximate analytical solution was presented by Jones et al. (2002a, 2003). to estimate a quantitative value of mass loss. The calculated results showed that the mass loss was directly proportional to the tunnel length, the diameter of projectile and the shear strength of target. Later, Beissel and Johnson (2000,2002). presented a surface abrasion criterion that is proportional to the relative sliding velocity and the normal stress between projectile and target. This criterion was incorporated in an axisymmetric finite-element algorithm with a fully rezoning method. It was found that numerical predictions were in a reasonable agreement with the available literature experimental data. Considering the velocity-dependent friction, an analytical incremental model was applied by Davis et al. (2003) to investigate the mass loss and to assess the projectile's performance in terms of its wear characteristics. Chen et al. (2010) also proposed an engineering abrasion model, based on the graphical discussion on the nose of the residual projectiles after high-speed penetration into concrete. Besides, utilizing Chen's model (Chen et al., 2010), further analyses were carried out by He and Chen (2011a), He et al. (2014) to discuss about the characteristic parameters of the projectile during penetration. It was demonstrated that the pulse shape of deceleration during high-speed penetration with mass loss was quite different from the “rigid” case. Moreover, taking into account scratch and heat melt effects pointed out by Jones et al. (2002a) and Davis et al. (2003) respectively, He et al. (2010b) suggested an empirical expression to estimate the mass loss rate with seven main influential variables, i.e. the initial nose shape, initial impact velocity, melting heat, shank diameter of a projectile, density and strength of the target as well as aggregate hardness of the target. The effects of these variables on the ultimate mass loss of a penetrator were compared, which provided useful information for engineering

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