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Study mass loss at microscopic scale for a projectile penetration into concrete

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ABSTRACT

Mass loss of the kinetic energy (KE) projectile results in a dramatic drop of DOP (Depth of Penetration) due to the change of nose shape. This is often observed in the high-velocity penetration into concrete, which significantly influences the penetration efficiency. In order to investigate the intrinsic mechanisms of mass loss, experiments were conducted on 30CrMnSiNi2A kinetic energy projectiles with an ogival nose penetrating concrete targets in the normal direction at a striking velocity of 843 m/s and 1400 m/s, respectively. Microstructural features of various sections, obtained from different locations of the residual projectiles recovered from concrete targets, were systematically characterized by using optical microscope, energy dispersive X-ray (EDX) detector and microhardness tester. Based on the experimental observations and analysis, evolution mechanisms of the microstructures induced by plastic deformation and high temperature during penetration were proposed. It involves formation of the mixed zone (MZ), the refined zone (RZ) and the original zone (OZ). Experimental evidences and analyses of the surface formation suggest that the thermal softening, material flow and eventual mass loss associated with high strains and high strain rates at high temperature are the main mechanisms of material failure during projectile penetration.

1. Introduction

Low-velocity penetration (<1000 m/s) into concrete with kinetic energy (KE) projectile has been studied systematically [1–5] by assuming the projectile as a rigid body. However, with increasing impact velocity (1000 m/s $< v <$ 2000 m/s), the mass loss of the projectile becomes more and more significant during the penetration process. Phenomena, such as nose abrasion, bending or breaking of the projectile resulting in the trajectory deviation as well as dramatic drop of DOP (Depth of Penetration), are observed in many experimental results [6,7]. The assumption of a rigid projectile penetration through concrete targets is inappropriate in the case of high velocity penetration. It is an indisputable conclusion that the unstable projectile structure induced by mass loss will significantly affect the performance of terminal lethality. Therefore, ensuring the integrity of projectile at high velocity impact becomes an imperative issue in the international research community. For further development of the earth penetration weapon (EPW), a clear cognition of the underlying mechanisms is required to the mass loss of a projectile during high velocity penetration.

With increasing the research interest in high velocity impact, a series of experimental studies as well as theoretical exploration have been carried out to reveal the mechanisms of the mass loss during penetration. Through the experimental work, Forrestal et al. [6,10] and Frew et al. [8,9] found that mass abrasion mainly occurred at the exterior surface of projectiles' nose. This was based on the six groups of penetration experiments with different CRH (caliber radius head) projectiles and uniaxial compressive strength of the concrete targets. The mass loss is up to 7% when the striking velocity exceeds 1200 m/s. Furthermore, Silling and Forrestal et al. [11] indicated a liner relationship between the mass abrasion and the initial kinetic energy of a projectile below the velocity of 1000 m/s based on the experimental data from Sandia National Laboratory (SNL). In consideration of the yield strength of projectiles, He et al. [12] and Yang et al. [13] investigated the penetration ability, stability and deformation of projectiles in high velocity impact. The results obtained from extensive experimental work showed that the mass loss of the projectile is closely related to the initial impact velocity, the dynamic mechanical property of penetrator, the category of the aggregate casted in concrete and

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other random factors. Basic phenomena during high velocity penetration were observed in those experiments, which support the hypotheses for theoretical research.

In the case of theoretical analysis, assuming that the rate of mass loss is proportional to the normal stress and the sliding velocity between projectile and concrete, Beissal et al. [14,15] developed an axisymmetrical mass abrasion model for carrying out the 3D finite element analysis. Jones et al. [16] proposed an abrasion model based on the assumption that the mass loss is caused by the heat produced by the sliding friction between projectile and concrete. Chen et al. [17] identified the hardness of aggregates having a significant influence on the mass loss after examining the experiment data from Forrestal et al. [6]. In combination of Jones' model [16] and Silling's model [11], He et al. [18] derived a model with seven main influential variables, i.e., the initial impact velocity, initial nose shape, melting heat, shank diameter of projectile, density and strength of target as well as aggregate hardness of target, which is the most successful one to predict the mass abrasion of a projectile. The abrasion effect for the projectile nose has a significant influence on penetration. There are several abrasion models developed to modify the variation of projectile nose, such as Davis et al. [19], He et al. [20], Wen et al. [21] Yang et al. [22] and Qian et al. [23]. Zhao et al. [24,25] and He et al. [26,27] analyzed the penetration processes considering mass loss based on the assumption that the nose maintained arc during the penetration with the minimum CRH equal to 0.5. Klepaczko et al. [28] gave a definition on the universal parameters of the rate of wear and the rate sensitivity of wear. Mu et al. [29] and Zhang et al. [30] conducted relevant experiments with the impact velocity up to 1600 m/s and proposed an engineering model to determine transition velocity into the semi-hydrodynamic penetration regime. Good consistency has been obtained between the existing theoretical calculations and experimental results, to some extent. However, due to the limitations of theoretical assumptions, most predictions on the new situation derived from the theoretical models do not provide satisfactory calculations. The existing method to predict mass loss by the simple assumption of material melting or curve fitting of the cited experimental data is inappropriate. Therefore, a clear understanding of the mechanisms of mass loss is essential for the establishment of reasonable theoretical assumptions and further analysis.

Involving with high temperature, high pressure and high strain-rate induced by high velocity, it is difficult to obtain or record some real-time data experimentally to support the theoretical analysis in the instantaneous penetrating process. Therefore, an efficient approach to analyze mass loss in microscopic level is imperative to further improve the penetration ability of EPW. The objective of this work is therefore to reveal the underlying mechanisms of mass loss of a projectile at a high striking velocity. Experiments were conducted on 30CrMnSiNi2A kinetic energy projectiles with an ogival nose shape penetrating into concrete targets in the normal direction with a striking velocity range of 800–1400 m/s. Specimens drawn from the residual projectiles were analyzed by optical microscope and scanning electron microscope with energy dispersive X-ray (EDX) detector to examine the metallographic structural evolution in detail along the surface depth affected. In addition, microhardness tests were undertaken to further obtain the gradient variation of hardness from the outer to the inner surfaces of the projectile. The mechanisms of mass loss were proposed and the dominant factors were identified.

2. Penetration experiments

2.1. Experimental setup

A 105 mm caliber smoothbore gun was used to launch a 60 mm diameter projectile to penetrate into concrete with a velocity in a range of 800–1400 m/s by the sub-caliber launching way. A reasonable mass charge was calculated according to the required striking velocity. A time-measuring system, containing a multi-channel time recorder and several aluminum foils used to provide signals for the time recorder, was placed at the flight trajectory of the projectile to obtain the striking velocity. In addition, two high-speed cameras were set orthogonally to record and measure the flight attitude, e.g. pitch and yaw angles of the projectile. All units were aligned and fixed to make sure that the projectile could hit the target normal to its surface. The experiment layout is showed in Fig. 1.

2.2. Projectiles and targets

The CRH = 3 ogive-nose projectiles, with a length of 300 mm and diameter of 60 mm, were machined using 30CrMnSiNi2A steel. The hollow structure was used to reduce launch weight in order to satisfy the impact velocity with the consideration of structural safety during launching and penetrating processes, as shown in Fig. 2. The concrete targets with limestone aggregate were casted in steel tubes of 1800 mm in diameter with the wall thickness of 10 mm, which were cured in standard conditions for 28 days. Three 150 × 150 × 150 mm cubes used for compressive strength tests were cored from the cured concrete inside the steel tube. Tests indicated that the concrete samples had a nominal unconfined compressive strength in a range of 40–45 MPa and a density of 2400 kg/m^3.

2.3. Penetration results

Eight experiments were conducted with relevant data recorded. In order to investigate mechanisms of the mass loss during penetration, two projectiles related to the minimum and the maximum velocities were recovered for further analysis. Fig. 3 shows the images of the ogive-nose projectiles tested at a velocity of 853 m/s and 1401 m/s, respectively. It is clear that the projectile subjected to the velocity of 853 m/s shows a negligible abrasion (Fig. 3(a)) and however, the projectile at the velocity of 1404 m/s must have experienced a grim penetration process featured with the nose shape significantly changed (Fig. 3(b)). Table 1 summarizes the experimental results of these two projectiles.

3. Microscopic analysis of the recovered projectiles

The high-strength alloy steel 30CrMnSiNi2A is widely used for manufacturing load-supporting structure, such as aircraft landing gear due to its excellent comprehensive properties. The other chemical compositions in the alloy steel are listed in Table 2, while its original metallographic structure is displayed in Fig. 4. It is found that the main composition of tempered sorbite structure has high

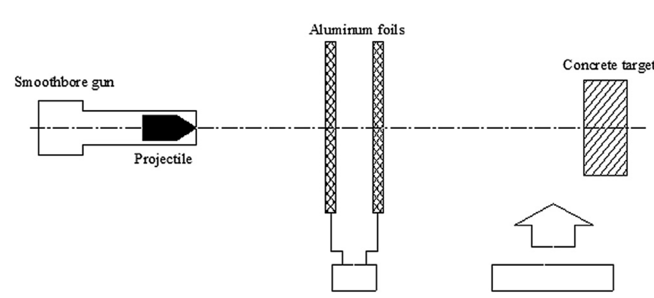

Fig. 1. Plan sketch of experiment layout.