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Microstructural observations on the terminal penetration of long rod projectile

Krushna Kumbhar*, P. Ponguru Senthil, A.K. Gogia

Armour Design and Development Division, Defence Metallurgical Research Laboratory, Hyderabad 500058, India

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ABSTRACT

Present study focuses on the terminal penetration of tungsten heavy alloy (WHA) long rod penetrator impacted against armour steel at an impact velocity of 1600 m/s. The residual penetrator and armour steel target recovered after the ballistic test have been characterized using optical microscope, scanning electron microscope (SEM) and electron probe micro analyzer (EPMA). Metallurgical changes in target steel and WHA remnant have been analysed. Large shear stresses and shear localization have resulted in local failure and formation of erosion products. Severe plastic deformation acts as precursor for formation of adiabatic shear band (ASB) induced cracks in target steel. Recovered WHA penetrator remnant also exhibits severe plastic deformation forming localized shear bands, ASB induced cracks and shock induced cracks.

1. Introduction

Penetration of long rod projectile is a complex phenomenon which involves erosion and deceleration of the rod and erosion and acceleration of the target [1–3]. The projectile material, density, impact velocity and the aspect ratio of the projectile are the main factors which affect performance of the projectile against a given target [4]. Similarly target material properties and density also influence the penetration. Projectile erosion begins when impact velocity exceeds a critical velocity [2,3]. In erosion regime, both the projectile and target are consumed during the course of penetration. Because of erosion, length of the projectile continuously decreases with increasing penetration. When the eroding projectile reaches a minimum L/D ratio, the projectile erosion comes to an end for a given impact velocity [3,5]. After reaching this minimum L/D ratio, projectile penetrates the target as a rigid rod. Several experimental and simulation studies have been carried out with different combinations of target and projectile materials and impact velocity to understand the penetration of long rod projectiles [1–9].

Penetration of long rod projectile in a target takes place mainly in three phases namely transient, steady state (primary) and non steady state (terminal) penetration [8]. Transient phase occurs during the initial impact of the projectile with the target generating high pressure and shock waves and lasts for a very short time [3,8]. Primary (steady state) penetration contributes almost the entire penetration of the projectile. In this regime, projectile kinetic energy is dissipated in the target as well as the projectile. Failure and flow of target and projectile materials (erosion) opposite to the direction of the penetration occurs creating the final crater. Both the penetration and projectile consumption occur at a constant rate resembling a steady state flow. However, experimental observations have concluded that while this stage is characterised by a steady state, it is not completely hydrodynamic [10]. Though contribution of steady state penetration is dominant in long rod penetration, significant length of the penetrator undergoes rigid or terminal penetration at the end [11,12]. In terminal phase, projectile erosion stops and the projectile penetrates as a rigid rod. Projectile deceleration occurs and the penetration continues until the projectile kinetic energy is consumed completely. Due to deceleration of the projectile, the pressure at target-projectile interface reduces continuously [3]. When the pressure drops below the dynamic yield strength of the target material, penetration comes to an end. Strength of the material plays a major role in this phase of penetration.

* Corresponding author. Armour Design and Development Division, Defence Metallurgical Research Laboratory, Kanchanbagh, Hyderabad 500058, India.
E-mail address: krushna@dmrl.drdo.in (K. Kumbhar).
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For projectiles with large aspect ratio, the transient phase can be neglected and total penetration can be given by Ref. [3].

$$P = P_s(Steady\ state) + P_r(Terminal) \quad (1)$$

P_s is the depth of penetration corresponding to the length (L_s) of the projectile that undergoes erosion and P_r is the depth of penetration corresponding to the rigid length of the projectile (L_r). At a given impact velocity, the projectile with a certain initial length L ($L > L_r$) starts eroding until it reduces to length L_r. Upon its length reaching L_r, it behaves as a rigid projectile. This rigid penetration resembles penetration of small arms projectiles where the penetration shows a high dependence on strength of the target.

Though lot of studies have been carried out on steady state and terminal penetration using scaled down tests, experiments involving full scale tests are rare in open literature. Metallurgical changes that occur during penetration can give some insights and clues about the mechanisms of deformation and failure at such high rates of loading. The post ballistic metallurgical studies on the long rod penetration are also limited in literature [4,5,7,13]. Present study describes metallurgical observations on recovered tungsten heavy alloy long rod remnant and target steel corresponding to terminal penetration and outlines possible deformation and failure mechanisms in both projectile and target.

2. Materials and experimental procedure

Armour steel used in the present study is a medium carbon low alloy steel. The chemical composition of the steel is given in Table 1. Mechanical properties of the steel are shown in Table 2. Projectile used in the test is made of tungsten heavy alloy (WHA) projectile with an L/D ratio of 16. Density and hardness of the WHA projectile are 17.5 g/cc and 510 VHN respectively. The ballistic test was conducted at an impact velocity of 1600 m/s and zero degree angle of attack. Target was a composite of ceramic (Alumina) and steel in front followed by stack of armour steel plates at back. The steel plates in the stack were sufficient in number to provide semi-infinite thickness. The thickness of the composite was kept such that the stack of armour plate at the back side was able to experience steady state penetration. It was also ensured that the transition from steady state to terminal phase occurs in the semi-infinite backing of armour steel. Residual penetrator and the steel crater were cut longitudinally and prepared for metallurgical characterization. 2% Nital was used as etchant for etching steel. Different locations in residual penetrator and armour steel crater were observed using optical microscope (OLYMPUS GS-51) and Scanning Electron Microscope)(FEI QUANTA 400) to understand the deformation and failure mechanism. Electron probe micro analysis (EPMA) also has been carried out to understand the compositional changes caused by the penetration in WHA. Micro hardness has been measured with OMNI TECH (MVH-SAUTO-550) at a load of 300 gm.

3. Results and discussion

3.1. Initial microstructure of WHA projectile and target steel

The initial microstructure of the WHA projectile is shown in Fig. 1. It consists of tungsten particles embedded in a ductile matrix of W-Ni-Fe-Co. Average size of tungsten particles distributed in the matrix has been estimated as 46 ± 13 μm by utilising the image analysis software Image tool 2.0. The average chemical composition of the WHA is given in Table 3. The SEM microstructure of armour steel used for this study is shown in Fig. 2. The microstructure exhibits tempered martensite which is characteristic of quenched and tempered heat treatment condition. Fine cementite particles precipitated in the decomposed martensite matrix caused by tempering can also be seen.

Table 2
Mechanical properties of armour steel.

Properties	
Yield strength/MPa	882 (SD 13)
UTS/MPa	991 (SD 07)
Elongation/%	16 (SD 02)
Reduction/%	65 (SD 01)
Hardness (VHN)	300–320

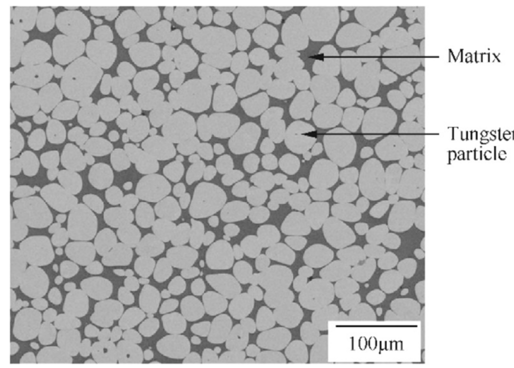

Fig. 1. SEM image showing initial microstructure of the WHA penetrator.

Table 3
Chemical composition of WHA (wt %).

	W	Ni	Fe	Co
WHA	86.8 (0.70)	8.4 (0.20)	2.1 (0.10)	1.15 (0.05)

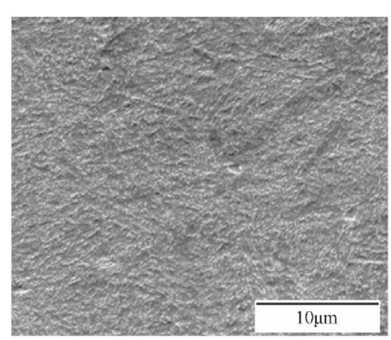

Fig. 2. SEM microstructure of stack steel plate showing tempered martensite.

Table 1
Chemical composition of armour steel.

Chemical composition/wt.%	0.28–0.33%C, 0.4–0.6%Mn, 0.1–0.25%Si, 1.3–1.5%Cr, 1.5–1.7%Ni, 0.3–0.5%Mo, 0.08–0.12%V, balance Fe