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Effects of hardness of steel on ceramic armour module against long rod impact

W.L. Goh[a,b], Y. Zheng[b], J. Yuan[b], K.W. Ng[a,*]

[a] School of Materials Science and Engineering, Nanyang Technological University, 639798, Singapore
[b] Temasek Laboratories, Nanyang Technological University, 50 Nanyang Drive, 637553, Singapore

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ABSTRACT

An experimental study and hydrocode simulation was conducted to investigate the correlation between hardness of steel and the ballistic performance of steel-encapsulated SiC armour modules against long rod impact. The armour module design composed of a SiC tile in confinement within 10 mm backing and 5 mm cover plates, which were made of AISI 4340 steel with varying hardnesses between HRC 30 to 50. The armour modules were subjected to normal impact by conical tungsten alloy long rods of 8.3 mm diameter and 115 mm length, at a nominal striking velocity of 1.25 km/s. A witness block of AISI 4340 steel was placed behind the armour module to capture the residual projectile. Failure analysis of the armour modules and the measurement of residual penetration in the witness blocks were applied to characterize ballistic performance of the ceramic armour modules. The different modes of failure of the backing plate and its influence on ballistic performance of the module were verified through visual inspection of test modules and analysis of high speed videos. Hydrocode simulation of the experiments using LS-DYNA was carried out to model the penetration and failure processes that occurred in the armour modules. The Johnson Cook model was applied in simulation of the steel confinement, accounting for the influence of hardness on JC model parameters. Results showed that increasing hardness of the backing enhanced the performance of the module while cover plate hardness had no influence within the range of hardnesses tested. This study paves the way for future studies to further understand the influence of steel hardness on the ballistics performance of steel-encapsulated silicon carbide (SiC) armour modules.

1. Introduction

While many studies have been conducted to understand the how the configuration of a ceramic armour module affects its ballistic performance [1–9], there has been relatively lesser work conducted on understanding the influence of material properties of the various components in an armour module on ballistic performance [10–15].

While armour configuration is essential for optimal performance, material properties will significantly influence ballistic performance. Espinosa et al. had conducted studies on interface defeat of long rod projectile into confined multi-layered ceramics. To achieve interface defeat, a thick cover plate and backing were used to maintain the confinement of the ceramic. It was concluded that ballistic performance of the ceramic armour was heavily influenced by the cover plate hardness where interface defeat could only be achieved when the cover plate hardness was above 53 HRC [10]. However it was noted that this understanding will need to be verified for scenarios with thinner cover plates, for practical applications. Strassburger et al. had conducted a series of experiments which compared the ballistic performance of SiC ceramics with different backing materials against 7.62 mm projectiles and found that strength of the backing layer influenced the duration of dwell phase heavily [11]. However, constant areal density was not factored into the study in order to quantify the influence of backing hardness on ceramic armour performance. Studies on alumina/metal laminates were conducted by Ubeyli et al, who concluded that hardness of metallic backing had significant influence, with AISI 4340 of 40 and 50 HRC producing the best performance [12–14]. These studies demonstrated that the hardness of armour components had great influence on ballistic performance. The current study aimed to extend the prior work to lighter module for practical application purposes and to compare samples made with the same areal density and material to remove confounding factors. For this purpose, experimental and simulation work were conducted to study the influence of the hardness of cover and backing plates of a steel-encapsulated SiC armour module on ballistic performance.

* Corresponding author.
E-mail address: kwng@ntu.edu.sg (K.W. Ng).

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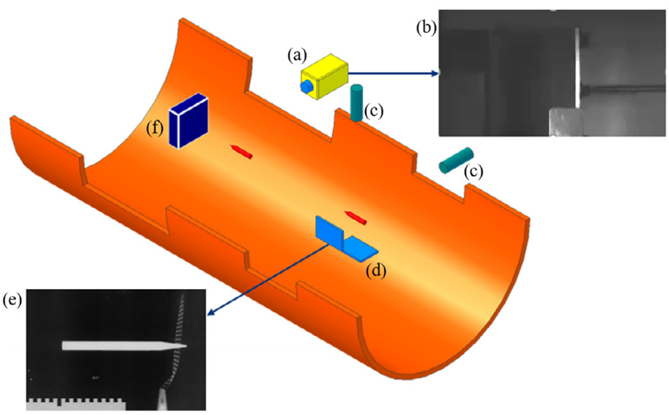

Fig. 1. Experimental layout of the ballistic test. (a) high speed imaging camera, (b) snapshot of high speed video, (c) flash X-ray imaging tube, (d) X-ray imaging plates, (e) an X-ray image of the projectile and (f) target.

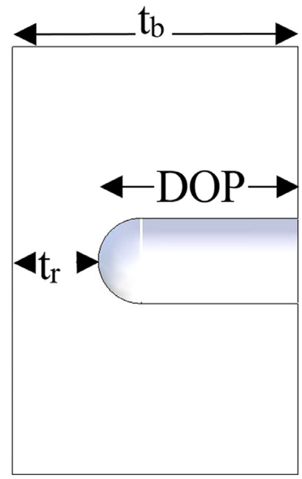

Fig. 2. Diagram of DOP measurement.

2. Experiment

Experiments were conducted at the Ma Jan High Speed Dynamic Laboratory, Temasek Laboratories, Nanyang Technological University, Singapore. The experiments were carried out on a two-stage light gas launcher, using projectiles made of W4Ni3Fe tungsten alloy with mass of 96 g and L/D ratio of 13.8. The nominal velocity was 1.25 km/s. The setup of the experiment was shown in Fig. 1, where a high-speed camera (SA-5 by Photron from Japan) was used to observe the projectile penetration process into a target and a flash X-ray system (SCF 150 by Scandifliash from Sweden) was used to measure the extent of pitch and yaw in the projectile. The velocity was captured with a laser measurement system (VMS 600 by Symes from France).

There were two parts to the experiment: (1) establishing the reference depth of penetration (DOP) data and (2) investigating the correlation between hardness of the cover/backing layers and ballistic performance of the armour module. The areal density of the armour module was fixed at 180 kg/m^2.

2.1. Materials

AISI 4340 steel of hardness values between 30 to 50 HRC was used for all the targets were supplied by ASCOMETAL. The ceramic used was silicon carbide (SiC) Grade F Plus from 3 M Technical Ceramic (previously ESK). Material properties were measured ($n = 2$ to 4) and mean values shown in Table 1, except for material density and young's modulus which was obtained from datasheet provided by the supplier.

2.2. Reference test

Reference DOP data was obtained through a series of DOP tests, where a projectile was launched into an AISI 4340 (untreated) semi-infinite steel block (150 mm diameter × 120 mm thick) with velocity ranging from 1100 m/s to 1350 m/s. After the tests, the steel specimens were sectioned and the DOP of the projectile was measured as described in Fig. 2, and plotted against velocity as shown in Fig. 3.

A total of 6 DOP tests were conducted with tungsten alloy projectiles against AISI 4340 steel. A best-fit line was drawn with an R^2 value of 0.93 indicating good linear correlation. The DOP-velocity relationship was consequently determined as shown in Eq. (1).

$$DOP = 0.1091v - 71.52 \tag{1}$$

2.3. Module test

To correlate hardness of the cover plate and backing to the ballistic performance of ceramic armour modules, a simplified armour module was designed as shown in Fig. 4. There were three main components in the armour module namely, (1) cover plate, (2) ceramic and (3) backing/confinement. Both cover plate and backing were made from AISI 4340 steel. The ceramic was Grade F Plus SiC, from 3 M Technologies (previously ESK) and was adhered to the backing with epoxy adhesive, Loctite NA3909.3. The cover plate was attached to the module with M8 screws at the 4 corners. The thicknesses of the cover plate, ceramic, adhesive and backing were 5 mm, 20 mm, 0.5 mm and 10 mm, respectively.

Each projectile was launched at the module in normal impact configuration as seen in Fig. 4. Residual projectiles were captured by a witness block (AISI 4340 steel, HRC 30, 150 mm diameter × 80 mm thickness) after penetration of the module. An air gap of 75 mm was left in between the witness block and the armour module. The ballistic performance of the module was then assessed based on mass efficiency, calculated using Eq. (2) as follows,

$$E_m = \frac{\rho_b p}{\rho_{st} t_{st} + \rho_c t_c + \rho_b p_r} \tag{2}$$

where ρ_b denotes the density of witness block, p is the reference depth of penetration i.e. the depth of penetration into witness block at same velocity; p_r is the residual penetration into the witness block

Table 1
Measured properties of materials used in experiment.

Materials	ρ_o(kg/m^3)	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Vickers hardness (kgf/mm^2)
4340 (HRC 30)	7850	210	850 ± 59	1020 ± 37	298 ± 7
4340 (HRC 40)	7850	210	1212 ± 4	1376 ± 3	412 ± 6
4340 (HRC 50)	7850	210	1424 ± 9	1713 ± 7	510 ± 3
Tungsten alloy	17,600	320	636 ± 11	902 ± 9	260 ± 10
Grade F plus SiC	3190	430	–	–	2450 ± 130