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Goh, Wei Liang

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**NANYANG
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**IMPORTANCE OF HARDNESS AND TOUGHNESS IN
CERAMIC ARMOUR**

GOH WEI LIANG

SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

2019

IMPORTANCE OF HARDNESS AND TOUGHNESS IN CERAMIC ARMOUR

GOH WEI LIANG

SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

18/3/2018

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Date

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Goh Wei Liang

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

18/3/2018

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A/P Ng Kee Woei

Authorship Attribution Statement

This thesis contains material from papers published in the following peer-reviewed journals where I am the first author.

Chapter 4 and 6 is published as Goh, W. L., Zheng, Y., Yuan, J., & Ng, K. W. (2017). Effects of hardness of steel on ceramic armour module against long rod impact. *International Journal of Impact Engineering*, 109, 419–426. DOI: 10.1016/j.ijimpeng.2017.08.004.

The contributions of the co-authors are as follows:

- A/Prof Ng provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript was revised by Dr Zheng and Dr Yuan.
- I designed and assembled the ceramic armour module and conducted the ballistic experiments at Ma Jan High Speed Dynamics Laboratory. I analysed the experimental results and calculated the mass efficiency after experiments.
- All computer simulations were carried out by me using the workstations in Ma Jan High Speed Dynamics Laboratory and I carried out the analysis.

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- I designed and assembled the ceramic armour module and conducted the ballistic experiments at Ma Jan High Speed Dynamics Laboratory with the help of Mr Zeng

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18/3/2018

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Goh Wei Liang

Abstract

Extensive studies on ceramic armour had been conducted since the late 1960s, laying down the foundations for ceramic armour studies today. However, most of the work done has focussed on small calibre projectiles; i.e. 7.62 mm projectile, with limited work on long rod projectiles. Of these, there is a lack of studies that investigate relationships between hardness and fracture toughness of ceramic armour module components. On top of that, there is no consensus in the community on the relationship between ceramic hardness and its ballistic performance. The overall objective of this study was therefore to understand the influence of hardness and fracture toughness of ceramic armour module components on the ballistic performance of ceramic armour against long rod projectiles.

The strategy to understand the correlation between hardness and toughness of various component of ceramic armour and its ballistic performance was through experimentation using surrogate long rod projectile against modified ceramic armour modules. Computer simulations using LS-Dyna were then applied to understand the mechanism and the role each material properties played within a ceramic armour system.

This study emphasised on the three primary components of a ceramic armour module: (1) cover plate, (2) ceramic and (3) backing plate.

Cover plate hardness did not affect the ballistic performance of ceramic armour module. The ballistic performance was reduced by decreasing cover plate fracture toughness due to the early loss of confinement pressure which resulted in premature dwell termination.

By increasing ceramic hardness from 20.6 GPa to 24.4 GPa, mass efficiency of the armour module increased from 1.52 to 1.73. In contrast, fracture toughness did not influence the performance of the module. However, fracture toughness of ceramic highly influenced the damage radius, i.e. damage condition of neighbouring tile. When fracture

toughness increased from 2.84 MPa.m^{1/2} to 6.99 MPa.m^{1/2} the damage radius reduced from 420 mm to 138 mm.

Backing plate hardness was observed to have the most significant influence on the ballistic performance of a ceramic armour module. When backing plate hardness increased from HRC 30 to HRC 50, the ballistic performance increased from 1.29 to 1.84, an increase of 43% in ballistic performance; as compared to 0 % improvement for cover plate hardness over the same range.

Through the work conducted, the following conclusions were drawn; hardness and toughness of the components in ceramic armour worked toward influencing the dwell time. The cover plate was observed to be of critical importance in establishing dwell while ceramic and backing plate contributed to sustaining the dwell.

Lastly based on the research findings, an optimized armour was designed. The cover plate was first optimized based on maximizing the dwell time to areal density ratio. It was followed by the optimization of the ceramic to backing ratio. The best configuration was determined based on dwell time and DOP measurement.

Lay Summary

There is a significant amount of work done on understanding ballistic performance of ceramic armour against low calibre projectiles such as rifle rounds. However, not much work has been carried out with high level projectiles such as long rod projectiles. Long rod projectiles are characterized by their large length to diameter ratios, typically above 10.

As material hardness (ability to resist permanent deformation) and fracture toughness (ability to resist cracking) do not go hand in hand, i.e. improving one would compromise the other, it is difficult to prioritize between hardness and fracture toughness when it comes to designing of ceramic armour. Moreover, there is a lack of information on the correlation of hardness and fracture toughness with ballistic performance of ceramic armour.

Therefore, the overall objective of this study was to understand the influence of hardness and fracture toughness of ceramic armour module components on the ballistic performance of ceramic armour against long rod projectiles.

Two approaches were taken for the study: (1) ballistic experiments and (2) computer simulations. Ballistic experiments were done to establish the correlations while computer simulations helped to explain the correlations.

This study emphasised on the three primary components of a ceramic armour module: (1) cover plate, (2) ceramic tile and (3) backing plate.

The most significant finding of study was that hardness and fracture toughness of the various ceramic armour module components influences projectile dwell time. Dwell is the phenomenon where a projectile is eroded on an armour surface instead of penetrating it. This phenomenon is the most efficient phase of defeating a long rod projectile. Therefore, by understanding how hardness and fracture toughness influenced projectile dwell, the

correlation between hardness and fracture toughness of ceramic armour component and ballistic performance of ceramic armour was understood.

Cover plate hardness did not influence ballistic performance of ceramic armour module. Reduced cover plate fracture toughness reduced ballistic performance of ceramic armour module due to premature dwell termination.

Increased ceramic hardness improved ballistic performance of ceramic armour by extending projectile dwell. On the other hand, increased ceramic fracture toughness was found to reduce damage on neighbouring tiles.

Increased backing hardness improve ballistic performance of ceramic armour by providing ceramic with better support, thus prolonging projectile dwell.

Through the work conducted, the cover plate was observed to be of critical importance in establishing dwell while ceramic and backing plate contributed to sustaining the dwell.

Lastly, based on the findings in this study, an optimized ceramic armour was designed by maximizing projectile dwell to cover plate weight ratio and minimizing residual projectile energy, i.e. projectile energy after penetrating the ceramic amour module.

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Abbreviations

<i>AD</i>	<i>Areal Density</i>
<i>AP</i>	<i>Armour Piercing</i>
<i>AT</i>	<i>Alekseevskii-Tate</i>
<i>AIISI</i>	<i>American Iron and Steel Institute</i>
<i>COD</i>	<i>Crack Opening Displacement</i>
<i>DOP</i>	<i>Depth of Penetration</i>
<i>E_m</i>	<i>Mass Efficiency</i>
<i>FD</i>	<i>Full Damage</i>
<i>FEM</i>	<i>Finite Element Method</i>
<i>HEL</i>	<i>Hugoniot Elastic Limit</i>
<i>HIP</i>	<i>Hot Isostatic Press</i>
<i>ID</i>	<i>Incipient Damage</i>
<i>JH</i>	<i>Johnson-Holmquist</i>
<i>JC</i>	<i>Johnson-Cook</i>
<i>L/D</i>	<i>Length-Diameter Ratio</i>
<i>MJHSDL</i>	<i>Ma Jan High Speed Dynamics Laboratory</i>
<i>PDEs</i>	<i>Partial Differential Equations</i>
<i>RHA</i>	<i>Rolled Homogenous Armour</i>
<i>SF</i>	<i>Surface Failure</i>
<i>SHPB</i>	<i>Split-Hopkinson Pressure Bar</i>
<i>SiC</i>	<i>Silicon Carbide</i>
<i>SPH</i>	<i>Smooth Particle Hydrodynamics</i>
<i>TiC</i>	<i>Titanium Carbide</i>
<i>V_{bl}</i>	<i>Ballistic Limit Velocity</i>
<i>WHA</i>	<i>Tungsten Heavy Alloy</i>
<i>WWI</i>	<i>World War I</i>
<i>WWII</i>	<i>World War II</i>

Chapter 1

Introduction

This chapter gives a brief history of the development of ceramic armour and the rationale for conducting of these studies. This chapter also gives a quick overview of the topic of discussion for each chapter and listed out the contributions of the work done in these studies.

1.1 Background

Military vehicles are a large user of armour. The concept of armoured vehicle can be traced back to WWI. Back in WWI, the armour was primarily 6 to 8 mm steel, providing the troops with a certain degree of protection. The widespread use of tanks began during WWII. It was during this period where engineers created the behemoth tank, packing tonnes of steel onto the vehicles, with the Maus (mouse) the champion of all, weighing 188 tonnes and having armour steel up to 240 mm thick. The vehicle was so heavy that most of the bridges could not hold its weight. With rapid improvement of the attacking capability of modern gun, the old method of packing more steel is no longer feasible. This means a new approach to armour development must be taken to defend against the new threat.

In comes the development of high performance ceramics in the late 1960's into 1970's where Wilkins et al. had done intensive study on ceramic armour [1–4]. The relative high compressive strength (compared to steel and titanium) and low density of ceramic makes it a good candidate for the role of armour. However, ceramic is not a direct replacement to metal as it sacrificed its fracture toughness for the high compressive strength. Thus, ceramic is never a standalone protective system, rather, it is always a component of a system [5–10]. Many studies had been conducted by specific research groups and US military. Early studies by Rosenberg et al. [11–16] had laid down today's foundation for ballistic armour design and testing. Ceramic material model was developed by Johnson and Holmquist [17–20] deriving the JH series of material model which is now commonly used for modelling of ceramic. Interface defeat study by Hauver et al. [21], [22] reverse ballistic and dwell study by Lundberg et al. [23–27] demonstrated the potential of ceramic armour.

These studies built the knowledge which we know today on ceramic armour. However, studies on influence of hardness and fracture toughness of various component of ceramic armour are few [28–30]. These studies focussed on the mechanism study. Issues such as size scaling [10], the influence of boundary conditions such as lateral confinement

[23], [31–33], prestress [34–36] and tile thickness [37], vary from the actual armour design which prevents direct applications. Therefore, in this study, the author seeks to expand these findings from the above studies onto practical armour solutions.

Balancing hardness and fracture toughness of a material is a challenging task as gaining in one will reduce the other. Knowing which is more important, hardness or fracture toughness, will assist ceramic armour designer to overcome the dilemma in selecting between hardness and fracture toughness in ceramic armour. Looking through literature, multiple studies tried to correlate ceramic hardness and its ballistic performance. The results on how the ceramic hardness influences the ballistic performance of ceramic varied significantly; where some indicated correlation between hardness and ballistic performance [38–40] and others had no correlation [41–44]. Basically, there is still no common consensus on the subject topic.

Looking beyond the studies correlating ceramic properties and performance, an interesting phenomenon, interface defeat, which was observed in the work conducted by Hauver et al. in 1993 [21]. He demonstrated that with correct configuration, the projectile could be stopped at the ceramic surface. Many others caught on to his work, studying this phenomenon of interface defeat and dwell [27], [37], [45–50]. Dwell is a phenomenon where projectile eroded on the surface of ceramic and interface defeat is where the entire projectile dwelled for the entire duration of impact process. Of those work, Behner et al. demonstrated experimentally that dwell occurs for thin cover plate [47].

1.2 Hypothesis

“This thesis tests the hypothesis that the hardness and fracture toughness of the cover plate, ceramic tile and backing plate influenced the ballistic performance of ceramic armour against long rod projectiles, through their ability to influence projectile dwell time.”

1.3 Objectives and Scope

This thesis aims to establish the correlation between hardness and fracture toughness of cover plate, ceramic and backing plate of ceramic armour and its ballistic performance. These objectives are achieved by means of ballistic experiments and computer simulations. The ballistic performance is assessed using mass efficiency and the mechanism is studied through simulations. By establishing the link between experiment results and the working mechanisms of the components, the author seeks to develop a thorough understanding of the role of hardness and toughness in a ceramic armour module. With these findings and insights, the work extends to provide guidelines on the design optimization of ceramic armour, extending the usefulness of these studies to practical application on armour design.

1.4 Dissertation Overview

The thesis addresses:

Chapter 1 presents the overview of the current state of art ceramic armour development and gaps observed by the author. The hypothesis and objectives are outlined in this chapter.

Chapter 2 reviews the literature with regards to ceramic armour. This chapter covers topics regarding the defeat mechanism of long rod projectile and studies involving ceramic armour. This chapter also includes the simulation methods and models commonly used for ballistics impact for metal and ceramic.

Chapter 3 provides a detailed description of experimental methodology used in the study; ranging from low strain rate quasi-static tensile test to high strain rate dynamic ballistic test. This chapter also includes the elaboration on the simulation details, i.e. material parameters and mesh size selection process.

Chapter 4 presents the findings on the influence of hardness and fracture toughness of cover plate on ballistic performance of ceramic armour. The correlations are elaborated through the understanding mechanism of cover plate.

Chapter 5 presents the findings on the influence of hardness and fracture toughness of ceramic on ballistic performance of ceramic armour. This chapter explores these factors on both single-tile modules and multiple-tile modules. This chapter also confirms the relation between ceramic hardness and JH-1 model strength parameters.

Chapter 6 presents the findings on the influence of hardness and fracture toughness of backing plate on ballistic performance of ceramic armour. This chapter provides answer to how backing hardness improve ceramic armour performance through analysis of ceramic failure mechanism and dwell to penetration criteria.

Chapter 7 investigates the process of ceramic armour optimization through simulation. The chapter presents a systematic approach to optimize a 3-component ceramic armour and discusses the shift in dwell termination and defeat mechanisms during the optimization process.

Chapter 8 concludes the thesis and address the contributions to the field from the work done in these studies. This chapter also includes recommendations for future work based on the conclusions drawn.

1.5 Findings and Outcomes

This research leads to several novel outcomes by:

1. Establishes correlation between hardness and fracture toughness of various component of ceramic armour and ballistic performance of ceramic armour module against long rod projectile through experiment and computer simulation.

2. Establishes the correlation between ceramic fracture toughness and damage radius.
3. Establishes correlation between ceramic hardness and strength parameters S1 and S2 of JH-1 model.
4. Develops a systematic approach to optimize a 3-component ceramic armour.

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Chapter 2

Literature Review

In this chapter, literature review is done on ceramic armour design. The review consists of three main components; 1) theoretical aspect of defeat mechanisms for armour against long rod projectile, 2) experimental aspect of armour study and 3) hydrocode simulation study of ceramic armour. The first part explores the well accepted theories within the field of ceramic armour and long rod projectile. The second part covers the experimental works that were done on ceramic armour, i.e. experimental designs and conclusions drawn from the experiments. The last part covers the background of simulation works on ceramic armour, laying down the foundation for the simulation work done in this study.

2.1 Ballistic testing

Ballistic performance variation occurs with different testing methodology. The two most well accept methods of assessment for ballistic performance are: (1) V_{50} experiments and (2) depth of penetration (DOP).

The V_{50} test was first developed by Wilkins et al. [1–2]. The experimental setup consisted of thin ceramic tile bonded to similar thickness metallic or composites backing plates and were tested against 7.62 mm AP rounds with small length-diameter (L/D) ratio. The performance of the ceramic tile was assessed by ballistic limit velocity (V_{bl}). V_{bl} is defined as the velocity limit which the target will perforate. In theory, the V_{bl} can be determined using two experiments which have impact velocity that are very close. However due to measurement errors and fluctuations in material properties, it requires a ridiculously large amount of experiments to obtain V_{bl} . Therefore, a probabilistic approach is taken, where a set of experiments, with at least 6 test data is taken. In half of the cases the target survives the shot, while the other half of the target is perforated. This approach is known as V_{50} , where the velocity is taken from the average of the highest non-perforation velocity and lowest perforation velocity. Still, this method of determining ballistic efficiency requires a significant number of experiments, which are both costly and time consuming. Moreover, the assessment methodology is sensitive to the ceramic weight percentage, further limiting the effectiveness of this method [3–4].

Rosenberg et al. [5] pointed out the previous method of screening is limited by its thin backing. Due to the lack of support from the backing, the tensile stress develops at the ceramic back surface, resulting in premature fracture; undermining the performance of the ceramic. Thus, Rosenberg et al. [5] and Bless et al. [6] suggested another technique using thick backing and later accepted by the community [7–9]. This technique is more straightforward. The user needs to measure the penetration depth into the thick backing, also known as witness block, and assesses the ballistic performance bases on the penetration depth. It allows lesser tests to be conducted and became a widely used method for ballistic performance assessment [6], [10–21].

For DOP method to be valid, the main requirement is that the backing material must be semi-infinite. A “semi-infinite” target is defined as being large enough in both its lateral direction and its thickness, to not influence the penetration experiment results. Rosenberg and Dekel [22] had conducted a series of studies through simulation with WHA projectiles with L/D ratio of 10 and 20 with impact velocity ranging from 1.4 - 2.2 km/s. They concluded that the diameter of target is approximately 25 times of projectile diameter and thickness should be around double of the penetration depth for it to not influence the penetration depth. Simulation and experimental work was conducted by Littlefield et al. [23] where they drew a conclusion of 15 times of projectile diameter for it to be considered as “semi-infinite”.

2.2 Long rod Projectile

A long rod projectile is made up of high density material from either tungsten heavy alloys (WHA) or depleted uranium. The word long in its name is defined by the L/D, where a projectile is considered long rod when its L/D ratio is greater than 10. The penetration process of a long rod projectile continues throughout the erosion of the process of the projectile till the rod is completely eroded. This process was hypothesized by Christman and Gehring [24] that the penetration process was divided into four stages as shown in Figure 2-1.

Figure 2-1. Four-phase of penetration model [24].

The first phase is the point where high-pressure shock waves are generated by the impact and deformation of projectile nose. This phase is very short, usually in the time which the projectile penetrates to a depth of few projectile diameter. The second phase is the quasi-steady state of penetration. This is the dominant phase for a long rod projectile, which is used for prediction of penetration depth. The third phase is known as secondary penetration where inverted projectile resulting in extra penetration. The fourth phase is the recovery phase where the target material rebound near the end of penetration process. The fourth phase is usually ignored as it is insignificant to the penetration process.

2.3 Defeat Mechanisms

2.3.1 Erosion

When a projectile impacts a ceramic tile, the ceramic tile fractures due to tensile stresses formed in the radial direction of the ceramic. This forms the ring cracks concentric to the impact site. These ring cracks then grow into Hertzian cone-cracks which extend throughout the tiles at angle between 25° – 75° . When the compressive stress exceeds the

ceramic strength, microcracks begin to form in the material below the projectile. Small fragments of ceramic are formed as a result. As the projectile forces its way through the fragments, the high hardness of the fragments erode the projectile. The erosion process was captured by experiments carried out by Hohler et al. [25]. The projectile was seen to erode in a similar manner as erosion in metallic target. The quasi steady-state mode of penetration and projectile's erosion rates were found to be similar to those in metals. Therefore, the penetration process can be described by the Alekseevskii and Tate (AT) model [26].

The model is defined by the following equations,

$$\frac{1}{2}\rho_p(V-U)^2 + Y_p = \frac{1}{2}\rho_t U^2 + R_t \quad \text{Equation 2-1}$$

$$\rho_p l \frac{dV}{dt} = -Y_p \quad \text{Equation 2-2}$$

$$\frac{dl}{dt} = -(V-U) \quad \text{Equation 2-3}$$

where ρ_p and ρ_t are the material density of projectile and target, V and U is the instantaneous velocity of projectile tail and penetration velocity, Y_p is the projectile strength and R_t is the target strength respectively.

2.3.2 Dwell

Dwell is a phenomenon observed in ceramics, where incoming projectile is defeated through radial flow of material on the surface of ceramic. When dwell occurs throughout the entire duration of the penetration process, it is known as interface defeat. Earliest work demonstrating interface defeat could be achieved was carried out by Hauver et al. [27]. In this work, long rod projectile was tested against heavily confined TiC ceramic with thick steel backing and a multi-layered shock attenuator in front of the ceramic tile. In this experiment, interface defeat was achieved, i.e. all of projectile was defeated at the

surface of ceramic. The projectile is seen to flow radially on the surface of ceramic in Figure 2-2.

Figure 2-2. Image of target after ballistic test (a) front confinement (cover plate) and (b) top face of ceramic [28].

Espinosa et al. [29] conducted similar experiments as Hauver, using prestressed SiC and 25 mm thick steel cover plate coupled with graphite layer above the ceramic and a through the experiment, it was concluded that cover plate hardness of at least HRC 53 was required to achieve interface defeat. As interface defeat requires very thick confinement and their designs are extremely bulky, they are not suitable for practical use. Thus, researchers place their focus on the dwell phenomenon instead.

Figure 2-3. Illustration of module design for interface defeat experiment [29].

Ceramic achieved dwell due to its high strength relative to the projectile. The dwell phenomenon was observed on multiple occasions through reverse ballistic experiments [30–35]. It was proven experimentally that dwell phenomenon is sensitive to impact velocity [36–38]. As seen in Figure 2-4, where dwell was observed for ceramic

impacted at 776 m/s while no dwell was observed for impact velocity of 956 m/s [39]. This velocity where dwell transit to penetration is known as transition velocity. It was demonstrated that transition velocity are influenced by a few conditions: (1) material properties of ceramic [28], (2) degree of confinement [30], [47] (3) presence of buffer [40–46], and (4) prestress [30], [48] . Among all these conditions the effect of buffer is most widely studied due to its ease of transferring to application. It is shown in Figure 2-5, that by adding a buffer in front of the ceramic, the transition velocity increased significantly from 776 m/s to 1484 m/s. As dwell phase is the most efficient phase in projectile erosion, increased transition velocity allows ceramic to maintain its efficiency against stronger projectile. This demonstrates the importance of having a buffer layer (also known as cover plate).

Figure 2-4. X-ray images for reverse ballistic impact at (a) 776 m/s and (b) 956 m/s [39].

Figure 2-5. X-ray images for reverse ballistic (a) impacted at 776 m/s without buffer and (b) 1484 m/s with buffer in front of ceramic [39].

2.3.3 Mechanisms during dwell to penetration transition

The mechanism which led to transition from dwell to penetration has been commonly accepted to be the softening of the material; i.e. damage accumulation within the comminuted zone, located beneath the impacted site [45], [49–51]. Lundberg et al. proposed that there are three level of damage accumulation; (1) incipient damage (ID) where damage is initiated at the location where maximum shear stress occurs on the axis of symmetry below ceramic surface and this region will grow toward the impact location, (2) full damage (FD) where the damage reaches the surface of the ceramic and (3) surface failure (SF) in which cone crack is initiated as seen in Figure 2-6. When the damage accumulation reaches SF, dwell terminates.

The condition of damage ceramic is shown in Figure 2-7, cone cracks and comminuted zone, the main damage region described in the theory by Lundberg et al. was

proven experimentally through post-mortem examination of recovered ceramics after long rod impact.

Figure 2-6. Critical levels of damage beneath the impact location of ceramic where (a) incipient damage, (b) full damage and (c) surface failure [38].

Figure 2-7. Damage condition of SiC after recovery from long rod projectile impact 6.35 mm diameter and 1600 m/s [52].

LaSalvia proposed criteria shift for onset of penetration based on the normalized thickness of the ceramic [53] (thickness is normalized against projectile radius). He hypothesized that there are at least three criteria. The first criterion is due to failure of ceramic top surface. This criterion is used to derive the analytical expression for dwell to penetration transition in “thick” ceramics [54–56]. The second criterion is when the backing undergoes compressive failure. This occurs when the normal stress at the back face of ceramic exceeds the compressive strength of the backing. This is more common in “thin” ceramic as radial stresses for thin ceramics are mostly compressive, the compressive stress would suppress the ceramic damage. The last criterion is caused by damage at the

back surface of ceramic extending towards the top surface coupled with the partial failure of backing. This partial failure of backing results in loss of confinement pressure and allowing displacement of damage ceramic thus terminating the dwell. The information is illustrated graphically in Figure 2-8. Dwell and penetration criteria are separated into three regions of normalized thickness; criterion one occurs when normalized thickness is greater than 6.4, criterion two occurs when normalized thickness is less than 2 and criterion three occurs when normalized thickness is between 2 and 6.4.

Figure 2-8. Graphical illustration of the three dwell/penetration transition criteria plotted in terms of critical mean impact stress p_m for penetration onset and normalized ceramic thickness [53]. This figure reprinted from the BALLISTICS 2005: 22nd International Symposium on Ballistics, 2005. Lancaster, PA: DEStech Publications, Inc.

2.4 Influence of Hardness and Toughness in ceramic armour system

Literature review was carried out on the various component of ceramic armour. In the below sections, studies involving the main component of ceramic armour: (1) cover plate, (2) ceramic and (3) backing, will be discussed and the gaps will be addressed.

2.4.1 Cover Plate

The effect of cover plate was first confirmed by the work of Lundberg et al. through his works on reverse ballistics. In his studies, it was demonstrated that a good cover plate can improve dwell transition velocity by 200 m/s and more [28], [33].

Behner et al. had conducted few works on cover plate layer. In this study, copper projectiles were tested against three types of cover plate: (1) copper, (2) aluminium and (3) polycarbonate. It was concluded polycarbonate had the best performance with the lowest AD [57]. Another published work from Behner et al. focussed on influence of copper cover plate thickness on unconfined ceramic with thick backing ballistic performance [40], [43] concluding that unconfined ceramic is able to sustain dwell with a right cover plate configuration. Pickup et al. also conducted similar work where effect of cover plate on dwell was studied through experiment with long rod projectile against ceramic backed by thick steel backing [58]. The cover plate was observed to improve ballistic performance between 1387 m/s – 1570 m/s, but having negative effect when the velocity exceeds 1700 m/s. These studies demonstrate the role which a cover plate plays in a ceramic armour. However, there is limited work which correlates between material properties and the performance of ceramic armour. The work by Espinosa et al. in which impact recovery experiments were conducted on confined multi-layered ceramic targets to identify materials and structural design issues in interface defeat of long rod tungsten heavy alloy (WHA) penetrators [29]. It concluded that a cover plate hardness of at least HRC 53 is required to achieve interface defeat.

These works addressed had either bulky test jigs or were scaled down for mechanisms studies which cannot be translated directly to practical armour design. Therefore, in this study, the author seeks to address the gap to correlate material properties of cover plate and ceramic armour performance under realistic armour design configuration.

2.4.2 Ceramic

There is no common consensus on the one property which determine the ballistic performance. Rosenberg and Yeshurun [59] mentioned in his study that ballistic efficiencies of ceramics increase with their normalized effective strength. While Abadjieva and Carton concluded that no difference between ceramic with marginal difference in hardness [60]. Kaufmann et al. was inconclusive of any single material properties that was able predict ceramic ballistic performance [61]. Hallam et al. [62] and Flinders et al. [63], [64] correlated V_{50} performance to Knoop hardness, however no such correlation when Campbell et al. carried out this comparison across various type of ceramic [65]. In the work by Moll and Wickert [66], no correlation between hardness and ballistic performance was observed when tested against long rod projectile. Hilton et al. [67] established a correlation between a combined factor of hardness and plasticity with transition velocity of SiC. Liu et al. proposed a combined hardness/density ratio as a mean to rank ceramics for armour application [68]. Across the work conducted by many researchers, there are two groups of conclusions: (1) correlation observed between ceramic material properties and its dynamic performance and (2) no correlation between ceramic material properties and its dynamic performance; researchers are torn between the conclusions. On top of that, most of these studies were conducted with thick backing which is different from practical ceramic armour configuration.

Therefore, in this study, the author seeks to answer this question of does ceramic hardness or fracture toughness influence ceramic ballistic performance in a ceramic armour module setup instead of solely looking at ceramic as a standalone piece.

2.4.3 Backing

Rosenberg et al. demonstrated that ceramic ballistic performance is influenced by backing thickness and strength when tested against 7.62 mm AP rounds backed with 80 mm steel backing [69]. Strassburger et al. compared ballistic performance of SiC against 7.62 mm projectile with three different backing materials (harden steel, aluminium and

composite) and concluded that dwell duration has correlation with backing layer strength [70]. Ubeyli et al. work shown 26% weight improvement of ceramic armour against 7.62 mm AP round when steel backing was replaced with composite backing and improvement in performance with increased backing hardness [71–73], where HRC 40 and 50 AISI 4340 steel gave the best performance. All these studies were tested against 7.62 mm AP projectile which has different defeat mechanism compared to long rod projectiles [74], [75].

Therefore, in this study, the author seeks to understand how backing hardness and fracture toughness influence ceramic armour performance when against long rod projectile, providing ceramic armour designers with design guidelines against higher level threats.

2.5 Constitutive model for metal and ceramics

In this section, material models Johnson-Cook (JC) for metal and Johnson-Holmquist (JH) for ceramics are described. These models are used in the simulation work done in the study.

2.5.1 Johnson Cook (JC) Model

JC model is a commonly used model for simulation of metal in ballistic penetration process. The material is subjected to a series of tests, i.e. quasi-static tensile test and Split-Hopkinson pressure bar (SHPB) test to derive an expression of material strength various strain rate and temperature. The JC model is governed by the following equation [76],

$$\sigma = [A + B\varepsilon_p^n][1 + C\ln\dot{\varepsilon}^*][1 - (T^*)^m] \quad \text{Equation 2-4}$$

where A is the yield stress, B is the strain hardening coefficient, ε_p is the effective plastic strain, n is the strain hardening exponent, $\dot{\varepsilon}^*$ is the normalized strain rate where $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ in which $\dot{\varepsilon}$ is the effective plastic strain rate and $\dot{\varepsilon}_0$ is the reference strain rate of 1.0, C is

the strain rate coefficient, m is the temperature softening exponent, and T^* is the normalized temperature where $T^* = \frac{t-t_0}{t_m-t_0}$ in which t , t_0 and t_m are instantaneous temperature, room temperature and melting temperature respectively.

The equation is sectioned into three parts, with first term representing the hardening behaviour of material through strain hardening process, second term representing the strain rate dependence effect of the material and third term representing the loss of strength of material due to thermal softening.

The JC model is used for modelling of ballistic experiments and had yielded good results [77–84] for various metallic materials, ranging from aluminium, steel to titanium.

A work conducted by Deniz and Yildirim established a set of empirical equations to correlate hardness of AISI 4340 to its JC model parameters [85]. The parameters were obtained through correlating experimental results for quasi-static behaviour from Banerjee [86], strain rate effect from Lee and Su [87] and temperature effect from Tanimura and Duffy [88]. The obtained data was best fitted, deriving the following equations,

$$A = e^{0.0355 \cdot \text{HRC} + 5.5312} [\text{MPa}] \quad \text{Equation 2-5}$$

$$B = 0.6339 + A [\text{MPa}] \quad \text{Equation 2-6}$$

$$n = 0.0172 \cdot \text{HRC} - 0.4144 \quad \text{Equation 2-7}$$

$$C = -0.0001 \cdot \text{HRC} + 0.011 \quad \text{Equation 2-8}$$

where A , B , n and C are the material parameters listed in Equation 2-4. The material parameters were validated against experiment results through a total of 100 shots against 4 different hardnesses steel with each steel with 5 different thicknesses and 5 shots for each configuration.

2.5.2 Johnson Holmquist-1 (JH-1) Model

Johnson and Holmquist had developed three models, namely JH-1 [89], JH-2 [90] and JHB [48], [91]. In this study, the model used is JH-1 model. This model is available in LS-Dyna and has been validated [89], [92]. The JH-1 constitutive model consists of three components: (a) strength model, (b) damage model and (c) pressure model. The models are shown in Figure 2-9.

The strength model representing the variation of ceramic strength proportional to hydrostatic pressure is seen in Figure 2-9(a). In JH-1, the pressure-strength relationship is represented in a simplified linear manner. The strength of material is retained during damage accumulation, $D < 1$, and fail instantaneously when $D = 1$. This approach to ceramic failure provided constant strength under high pressures and large plastic strain, which is essential for simulation of dwell and interface defeat, a phenomenon which is observed in SiC experimentally [40], [42], [70].

Figure 2-9 Graphical representation of JH-1 Model (a) strength model, (b) damage model and (c) pressure model [89].

The strength model is shown in Figure 2-9(a), where T represents the maximum hydrostatic tensile pressure a material can withstand, while S_1 and S_2 are the strengths of intact material ($D < 1$) when $\dot{\epsilon}^* = 1.0$ at compressive pressures P_1 and P_2 respectively. After failure of material ($D = 1.0$), the gradient of failed material strength is α , and the maximum failure strength is $S_{\max}^f$. There is a strain rate constant, C , where strength of material at other strain rate is,

$$\sigma = \sigma_0(1.0 + C \ln \dot{\epsilon}^*) \quad \text{Equation 2-9}$$

The damage model is shown in Figure 2-9(b), where the accumulated damage for failure is,

$$D = \sum \Delta \epsilon_p / \epsilon_p^f \quad \text{Equation 2-10}$$

where $\Delta \epsilon_p$ is the increment of equivalent plastic strain and ϵ_p^f is the equivalent plastic strain at failure under a constant pressure, P . The failure strain is defined by,

$$\epsilon_p^f = \phi(P + T) \quad \text{Equation 2-11}$$

where,

$$\phi = \epsilon_{\max}^f / (P_3 + T) \quad \text{Equation 2-12}$$

The pressure model is shown in Figure 2-9(c), where the hydrostatic pressure when intact ($D < 1.0$) is,

$$P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \quad \text{Equation 2-13}$$

where K_1 , K_2 and K_3 are constants and $\mu = \frac{V_0}{V} - 1$ where V_0 and V are initial volume and current volume respectively.

At the point of failure ($D=1$), bulking can occur in the ceramic, resulting in an additional incremental pressure ΔP , thus

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P \quad \text{Equation 2-14}$$

where pressure increment is determined from energy considerations.

2.6 Hydrocode Simulation

2.6.1 Finite Element Method

Mesh-based method is the primary computational methodology in engineering computational mechanics. It is commonly used for solving of partial differential equations (PDEs). These PDEs is solved using approximation of equations based on discretisation. The approximated PDEs are solved by using numerical methods known as finite element method (FEM). FEM is ideal for tracking the material movement and deformation for low distortion cases, therefore, it is often used to represent solid structures. The advantages of FEM are computational efficiency and well-established theory. The disadvantage of FEM is that the element can be extremely distorted which affects the integration timestep and accuracy of results. This problem is solved using erosion, a numerical technique, to remove highly distorted element without interrupting the simulation.

2.6.2 Smooth Particle Hydrodynamics

Meshfree method are introduced to address problems faced by mesh-based method; such as free surface problems and large deformations. A common meshless method is the Smoothed Particle Hydrodynamics (SPH), where a set of particles with material properties are designed to behave based on governing conservation equations. SPH is stable for arbitrary distributed nodes and is good in dealing with large deformation while the accuracy

depended on the smoothing function [93]. This method is initially developed by Lucy et al. to simulate astrophysical problems [93–100].

The advantages of particle meshless method over conventional methods are, (1) the analysed domain is discretised with particles that are not connected with a mesh, thus able to provide simple and accurate solution for large deformations, (2) the discretisation of complex geometries is simpler and (3) the physical values of particles path are easier to track and assess, therefore easier to determine free surface of movable interfaces or deformable boundaries [101]. These advantages make SPH suitable for high strain rate and large deformation problem, i.e. hypervelocity impact. However, SPH needs to allocate resources to determine which particles interacts with one another within its influence sphere. This process is more expensive than mesh-based Lagrange methods with similar resolution.

2.6.3 FEM-SPH coupling

To overcome the limitations of both FEM and SPH, some researchers were trying to use both methods to their advantages [102–104]. In recent years, a new method *DEFINE_ADAPTIVE_SOLID_TO_SPH was developed and incorporated into LS-Dyna [105]. The method involves calculation in FEM, and when the elements are highly distorted, these elements are converted into SPH, where the stress experienced by the FEM element is transferred to the SPH particle. This provides a work around for the large distortion of FEM element and large computation time for SPH particles, improving the computation efficiency [106–108].

2.7 Summary

Previous researches on ceramic and ceramic armour components had been reviewed together with the dwell mechanism. Most of the works reviewed were either based on smaller projectile, i.e. 7.62 mm AP round or confined with heavy jigs. Small number of works were carried out on long rod projectile and ceramic armour configurations.

Moreover, it was reported that performance of ceramic is highly influenced by its test configurations, i.e. its confinement, cover plate used, and backing used, therefore studies based on realistic ceramic armour design needs to be used to answer some of the questions. This literature review sheds light on factors which potentially influence ceramic armour performance and provides the basis for this work.

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Chapter 3

Methodology of Study

In this chapter, the first section discusses about various type of material characterization done on metal and ceramic materials. These materials are integrated into different part of the ceramic armour module. The second section of the chapter will discuss the method used for conduct of ballistic testing and the various equipment used to extract valuable information from the ballistic experiment. The third section of the chapter will discuss hydrocode simulation, establishing the methods used in model building and material models such that accurate simulation of the penetration process is created. These lay down the groundwork required for establishing the correlation between hardness/toughness and ballistic performance of ceramic armour.

3.1 Material Characterization

In this section, the methods used for measurement of material properties of steel and ceramics are discussed. The material properties measured are hardness, fracture toughness, tensile strength and dynamic compression strength. The methods chosen are well established and well accepted in this field of study.

3.1.1 Hardness Measurement

Hardness of a material is a determination of how resistant a solid is to permanent deformation caused by a compressive force. In this study, the hardnesses of steel and ceramic were measured using the equipment Vickers Hardness tester FV-800 by Future-Tech, Japan. An image of the equipment is shown in Figure 3-1. Two parameters were set in hardness measurement, i.e. load and dwell time. The load is the amount of force exerted on the surface of the material while the dwell time is the amount of time which the load is being held. The dwell time ensures the material has sufficient time to “set”, ensuring consistent readings. Vickers indenter was used, and its geometry is shown in Figure 3-2. The tip of the indenter is made of diamond, whose high hardness ensured minimal deformation to the indenter during the loading on the tested material for maximal accuracy in hardness measurement.

Figure 3-1. An image of the hardness tester.

Figure 3-2. Geometry of Vickers indenter tip [1].

The specimen was first polished to mirror finish with surface roughness of $Ra \leq 0.2 \mu\text{m}$ as seen in Figure 3-3. The phenomenon of load dependency of hardness is observed in many experiments [2–6], which is known as indentation size effect. Although, this indentation size effect is more commonly observed for lower load, the hardness of the specimen in this study was measured at 3 different loads to be certain. As the equipment has a maximum magnification of 20x, the recommendation according to E384-11 [7] is minimum size for the diagonal of indent is $34.5 \mu\text{m}$. When indented with 3 kgf of load, the measured indent was $40.8 \mu\text{m}$, which is close to the minimum indent size, thus, any load of 3 kgf and below is not considered. The results of measured hardness are shown in Figure 3-4. The results reported are the average of three readings of a SiC specimen, where the measured hardness was similar for 10 kgf and 20kgf of load, while slightly higher hardness was measured when using 3 kgf of load.

As SiC is brittle, an additional consideration must be considered, the spalling of tiles. As seen in Figure 3-5, the SiC tile spalled when measured at 30 kgf of load. Occasional spalling was observed for 20 kgf of load. Therefore, the selected load was set as 10kgf to avoid spallation.

Figure 3-3. Picture of polished steel (left) and ceramic (right) specimen before indentation test.

After the indentation process, an indent imprint was left on the surface of the specimen. The hardness was obtained by measuring the diagonal of the indent imprint as seen in Figure 3-6. The formula to obtain Vickers hardness is as follow,

$$HV = 1.854 \frac{P}{D^2} \quad \text{Equation 3-1}$$

where P is load given and D is the average length of the two diagonals, D1 and D2, seen in Figure 3-6. HV unit is either kgf/mm^2 or GPa. For steel specimens, the more common unit for hardness was HRC, the conversion from HV to HRC is carried out based on conversion standard ASTM E140-02 [8].

Figure 3-4. A plot of measured hardness against different loading force on SiC specimen.

Figure 3-5. Images of the indents of SiC tiles under (a) 10 kgf and (b) 30 kgf loading.

Figure 3-6. An image of the indent, where D1 and D2 was the diagonal measured for hardness reading.

3.1.2 Fracture Toughness Measurement (Ceramic)

Ceramics have high hardness and low fracture toughness, usually less than $10 \text{ MPa.m}^{1/2}$. Fracture toughness measurement using indentation method is widely applied on ceramic [9], hence, it was used in this study. A comparison between the indent for a steel specimen and a ceramic specimen is shown in Figure 3-7. As seen from the images, the ceramic had fine cracks extending from the tips of the indent due to its low fracture toughness while steel did not show any cracks due to its high fracture toughness. The length of the cracks is an indicator of fracture toughness of the ceramic. According to standard JIS R 1607 [10], the equation for calculation of fracture toughness is,

$$K_{Ic} = 0.026 \frac{E^{1/2} P^{1/2} a}{c^{3/2}} \quad \text{Equation 3-2}$$

where E is the Young's modulus of the specimen, P is the applied load in N, and $2a$ is the average of the diagonal of the indent in mm and $2c$ is the average of the crack length in mm, shown in Figure 3-8.

Figure 3-7. Image of indentation on steel specimen (left) and ceramic specimen (right).

Figure 3-8. An illustration of the indent with crack indicated in red for the measurement of fracture toughness in ceramics.

3.1.3 Fracture Toughness Measurement (Steel)

Metal having higher fracture toughness, indentation method discussed in Section 3.1.2 is not suitable to be used on metal. Therefore, the method of 3-point bending of single-edge notched sample according to ASTM E399-09 [11], is applied for fracture toughness measurement of metallic materials. The test is carried out using Instron 8801 fatigue testing system as shown in Figure 3-9.

Figure 3-9. A picture of Instron 8801 fatigue testing system.

A typical specimen for fracture toughness measurement is shown in Figure 3-10. The specimen had a unique V-shaped notch at the centre of the specimen. The V-shaped notch acts as a stress concentration point, such that the specific fracture point could be determined.

Figure 3-10. Image of the fracture toughness test specimen.

The test consisted of two phases: (1) cyclic loading for crack formation and (2) 3-point bending. The cyclic loading created a crack of a specific length, either 0.025 of the width of the specimen or 1.3 mm, whichever is larger. The crack length was measured using a Crack Opening Displacement (COD) gauge as seen in Figure 3-11, where the COD gauge was held in place with the attachable knife edge. Once the crack length reached the pre-determined length, the cyclic loading stopped. This was followed by 3-point bending test to failure to measure the force required for the crack to propagate through the specimen.

Figure 3-11. COD gauge attached to the attachable knife edge for measurement of crack length.

Figure 3-12. An image of specimen after 3-point bending, where the fracture crack was observed at the tip of the notch.

Figure 3-13 shows the cross-sectioned view of the specimen. From the cross-sectioned view, two distinct zones were observed. The zones were caused by the two phases of the experiment. The first zone was caused by the cyclic loading phase which created a crack from the tip of the V-shaped notch. The second zone was the fracture surface which was caused by the 3-point bending test. Due to the nature of the crack, the shade for each zone is slightly different as seen in Figure 3-13. The actual value of the pre-crack length was measured after the test. The pre-crack length was unequal across the thickness of the specimen; thus, the pre-crack was taken to be the average of 3 readings, 1 mid-thickness and 2-quarter thickness.

The calculation of the fracture toughness is based on the following equation,

$$K_Q = \frac{P_Q}{B\sqrt{W}} \cdot f\left(\frac{a}{W}\right) \quad \text{Equation 3-3}$$

where,

$$f\left(\frac{a}{W}\right) = 3\sqrt{\frac{a}{W}} \cdot \frac{1.99 - \left(\frac{a}{W}\right)\left(1 - \left(\frac{a}{W}\right)\right)\left[2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right]}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{3/2}} \quad \text{Equation 3-4}$$

for which P_Q is the force, B is the specimen thickness, W is the specimen width, and a is the pre-crack length.

Figure 3-13. Sectioned view of the specimen after fracture.

3.1.4 Quasi-Static Tensile Test

Tensile test was conducted using Instron 5500R with 50 kN load cell. The test conducted was based on the ASTM standard E8-03 [12]. The dimensions of the specimen are shown in Figure 3-14 below. The gauge length, width and thickness of the specimen was 49.75 mm, 5 mm and 5 mm respectively.

Figure 3-14. Orthographic drawing of metallic tensile test specimen where dimensions are given in mm.

Figure 3-15 shows the experiment setup of a tensile test. An extensometer was used to obtain the strain during the initial phase of tensile test to reduce strain measurement inaccuracy caused by equipment. The extensometer was removed after 5% of measured strain, while the strain for remaining of the specimen was calculated by the system. The strain rate was fixed at 10^{-4} s^{-1} to ensure the process was a quasi-static process.

Figure 3-16 shows the comparison between the tested and untested specimen. The crack in the narrow region of the specimen and the increased length was due to plastic deformation during the test. Figure 3-17 shows a typical plot of experiment result. Through the plot, the Young's modulus, yield strength, maximum tensile strength and failure strain were obtained.

Figure 3-15. Experimental setup for tensile test.

Figure 3-16. Image of specimen (a) before testing (b) after testing.

Figure 3-17. A typical tensile test result plot.

3.1.5 Split Hopkinson Pressure Bar (SHPB)

As the ballistic experiment was conducted under high strain rate $> 10000 \text{ s}^{-1}$, the dynamic properties of the materials must be obtained. The dynamic properties were obtained through SHPB test. Figure 3-18 shows a schematic of the experiment setup. The system comprised of a striker, an incident bar, a transmission bar, and a momentum trap bar. The measurement system included Wheatstone bridges, a strainmeter and an oscilloscope. The striker was used to generate a pulse of compressive stress wave by impacting onto the incident bar. The stress wave was transmitted to the specimen through the incident bar. The stress wave would then propagate through the specimen into the

transmission bar and finally being carried away by the momentum trap bar and the momentum trap. High strength maraging steel was used for the bars. The length of the incident bar and transmission bar were 1.8 m and the striker was 0.4 m. Tungsten carbide plates were placed between the specimen and the bars to prevent yielding at the bars end.

The stress wave was detected by the strain measurement system composed of (1) strain gauge, (2) Wheatstone bridge and strainmeter, and (3) oscilloscope recorder. The strain gauges were adhered at the middle of the incident bar and the transmission bar. Each bar had two strain gauge place directly opposite of one another. The strain gauges used had a gauge resistance of $120\ \Omega$ and a gauge factor of 2.18 from Tokyo Sokki Kenkyujo Co. Ltd, Japan. The strain gauges were connected to a Wheatstone bridge with the set up shown in Figure 3-19 then to a strainmeter. The output of the strain from the strainmeter was recorded by an oscilloscope recorder.

Figure 3-18. Schematic of a Split-Hopkinson Pressure Bar setup for dynamic compression study.

Figure 3-19. Illustration of opposite half bridge setup for strain gauge and Wheatstone bridges [13].

The bars were first aligned together, to allow good transmission of the stress wave across the incident and the transmission bar. The alignment was checked using a blank test without a specimen. If the bars were in good alignment, only incident pulse and transmitted pulse would be observed, and if there is a misalignment in the bars, a reflected pulse would be observed in the incident wave signal as seen in Figure 3-20.

(a)

(b)

Figure 3-20 (a) Stress wave in bars were in good alignment and (b) stress wave in bars when misaligned [14].

The obtained data was processed into stress and strain data for it to be appreciated. Assuming no dispersion of stress waves, i.e. the readings measured at strain gage were

equal to the strains experienced at bar ends, 1-D stress wave theory relates to the particle velocities at both ends of specimen to the captured strain pulses seen in Figure 3-21.

The strain rate, engineering strain and engineering stress are defined by the following equations,

$$\dot{\varepsilon} = \frac{2C_B}{L_s} \varepsilon_R(t) \quad \text{Equation 3-5}$$

$$\varepsilon = \frac{2C_B}{L_s} \int_0^t \varepsilon_R(t) dt \quad \text{Equation 3-6}$$

$$\sigma = \frac{A_B}{A_S} E_B \varepsilon_T(t) \quad \text{Equation 3-7}$$

where ε_R and ε_T represent reflected and transmitted strain respectively, C_B , E_B and A_B are sound speed, Young's Modulus and the cross-sectional area of the bar material, L_s and A_S are length and cross-sectional area of specimen.

Figure 3-21. Testing section of SHPB. The strain measured at strain gage position is equivalent to strain at bar-specimen interface assuming no wave dispersion according to 1D stress wave theory.

3.2 Ballistic Experiment

In this section, the whole process of ballistic testing will be described. The launching system, target placement and targeting, the diagnostic system, the method of fabrication for target, ballistic performance assessment and materials used will be discussed in this section.

3.2.1 Two-Stage Gas Launcher

The ballistic experiment was conducted in the Ma Jan High Speed Dynamics Laboratory (MJHSDL), using a two-stage gas launcher from Thiot Ingenierie, France. Figure 3-22 shows an image of the gas launcher which was driven using high purity helium gas.

Figure 3-22. Image of gas launcher in Ma Jan High Speed Dynamics Laboratory (a) image taken from the gas launcher end and (b) image taken from target chamber end.

A schematic drawing of the launcher system is shown in Figure 3-23. The two stages were the pump tube and launch tube sections. There were two phases in the launch firing. In the first phase, piston was driven forward by the released of high pressure gas stored in the reservoir, which compressed the gas in the pump tube to extremely high pressure, up to 4000 bars, at the high-pressure component (HP), providing the driving force to accelerate the projectile along the launch tube. Upon exiting the launch tube, the sabot would separate from the projectile in the expansion chamber, leaving the projectile to impact the target in the target chamber. The two-stage gas launcher can launch projectiles at velocity up to 1.4 km/s. In the experiments conducted, the projectiles were launched at velocity between 1.0 – 1.4 km/s.

Figure 3-23. Schematic of two-stage gas launcher system.

The gas pressure setting was determined using a software provided by the manufacturer, Cesar32, where all the parameters of the launcher such as projectile weight, piston weight, reservoir pressure, pump tube pressures and etc, were input into the numerical simulation software to predict the experiment velocity outcome. The results of the simulation software were calibrated against two to three shots for accurate prediction.

3.2.2 Diagnose system in Ballistic Experiment

The experimental setup for the ballistic test is shown in Figure 3-24 below. The projectile was launched towards the ceramic armour module along the direction indicated in the image. The ceramic armour module was placed in the target chamber, which is shown in sectioned view for the ease of visualisation. Due to the fragments generated during the penetration process, the target chamber wall was made up of 20 mm thick steel wall while the viewing window was a 30mm thick ballistic resistance glass for protection purpose.

The diagnose system for ballistic experiments in the MJHSDL had three equipment, i.e. (1) velocimeter, (2) flash X-ray imaging system, and (3) high-speed imaging camera, all seen in Figure 3-24.

Figure 3-24. Schematic of the layout of ballistic experiment setup.

3.2.2.1 Velocimeter

Velocity of the projectile was measured using laser measuring system VMS 600 as seen in Figure 3-25. The illustration of the mechanism of the velocity measurement system is shown in Figure 3-26. Two parallel beams of laser were setup perpendicular to the flight direction of the projectile. The other end of the laser beams were receivers. When the projectile passed through the laser system, the projectile would block the laser beam, sending a signal to the velocity meter. As the distance between the two laser beams was calibrated, the time difference between the blockades of the signals of the laser beams would be the time taken for the projectile to pass through the distance between the two laser beams, allowing the projectile velocity to be measured.

Figure 3-25. A picture of the velocimeter used for measurement of the projectile velocity.

Figure 3-26. Illustration of the laser velocity detector working mechanism.

3.2.2.2 Flash X-ray Imaging

Flash X-ray imaging system was SCF 150 from Scandiflash AB, Sweden. Flash X-ray imaging system provided a snapshot using radiography. The flash X-ray system used 150 kV high voltage to generate a pulse of X-ray creating an image on the reusable X-ray film from DÜRR NDT, Germany. To create the image, the X-ray was blocked off, creating a negative image. The X-ray pulse penetration capability was affected by thickness and density of the target material.

To achieve imaging at a precise moment, two techniques were used to achieve accurate and valid measurement, i.e. (1) electronic triggering system and (2) time delay.

The electronic triggering system using a copper foil is seen in Figure 3-27. The foil consisted of two separate electrical pathways printed on an insulator film. The pathways were separated by a gap of 2mm. A voltage of 12V was applied across the two pathways by connecting the trigger cable to the terminals. The foil was attached to a Styrofoam block such that it remained in place during the shot. When the projectile perforates the film, it would act as a bridge to connect both circuits sending a trigger pulse in the form of electrical signal to the control system, activating the X-ray tubes, capturing the image.

The time delay would be added before the capturing of image from the time of triggering signal. The calculation of the delay was based on the expected velocity of projectile and the distance away from the trigger foil. This method was used to capture image for post-penetration phase such as the image shown in Figure 3-28. Trigger foil cannot be used for such shots as ceramic dust and hot metal stream will destroy the foil without triggering the flash X-ray. The challenge was to estimate the time which the projectile required to penetrate the target as it had different velocity in different material, thus requiring multiple shots to capture the perforated target image.

Figure 3-27. Image of trigger foil for the triggering of the flash X-ray system.

The advantage of the X-ray system was its ability to provide sharp images for pitch/yaw measurement. On top of that, as this imaging technique used X-ray, it was not affected by the bright flash generated during penetration process.

The pitch and yaw of projectile are important information to ensure the validity of the test results. The pitch and yaw had to be kept below 2° [15], [16] for the test results to be considered valid. This information was obtained using flash X-ray system. The image of the projectile was captured with a reference as seen in Figure 3-29. The reference was calibrated before the shot with a laser alignment system and the pitch/yaw was measured using the software D-Tect. This allowed the measured pitch/yaw to have an accuracy of $\pm 0.2^\circ$.

Figure 3-28. X-ray image of projectile and ceramic armour module after penetration process.

Figure 3-29. An image captured using flash X-ray to measure the projectile pitch.

3.2.2.3 High Speed Camera

High speed camera was used to capture the process of projectile penetration of armour module. The model was SA5 from Photron, Japan. The high-speed camera had the capability to capture up to 1,000,000 fps. For the experiments, 150,000 fps, 1/150,000 sec exposure time was used with a 256 by 144 pixel window as seen in Figure 3-30. The recording options were selected to allow at least 2 seconds of recording time and sufficiently large window to capture the penetration process of the target by the projectile.

Figure 3-30. Image from high speed video recording.

As the recording was done at very high frame rate, specialized non-flicker LED lights were used for illumination of the target for consistent light intensity for the recording duration. High speed imaging allowed the user to obtain information such as time for projectile to penetrate the target, deformation profile of the backing and cover plate etc. A piece of white matt paper is placed behind the target, away from the high-speed camera, to increase the contrast for a better image.

3.2.2.4 Target Positioning

The target was placed at around 5 m away from the muzzle of the launch tube, which required precise aiming for the projectile to impact on to the centre of the target to provide accurate results. This was done by a laser alignment system shown in Figure 3-31. The parts of laser alignment system were purchased from Edmund Optics. The laser aiming system consisted of two separated adjustable platform stages allowing the laser to be

adjusted in the vertical and horizontal direction. The laser was fixed on the stage through a mount, with tri-directional adjustment to control the tilting of the laser beam. The aiming system was placed before the launcher onto a stable platform. The laser was calibrated such that it passes through the centre of the gas launcher and the position was checked against a DOP test, where the position was marked and checked against the position which the projectile enters the DOP target. This allowed the projectile to impact the target with precision of ± 3 mm from the desired impact point. The final target placement is seen in Figure 3-32, where the laser point indicated the impact point of projectile.

Figure 3-31. Image of laser system for target positioning.

Figure 3-32. Image of target positioning aligned against laser.

3.2.2.5 Projectile

The projectile that was used for testing is a tungsten alloy long rod. The dimensions of the projectile are shown in Figure 3-33. It was a conical long rod projectile, where its diameter was 8.3 mm. The length of the projectile was 115mm, giving it L/D ratio of 13.8. It was made of an alloy with 93 % Tungsten with 4 % Nickel and 3 % Iron. The typical yield strength of such alloy was 700 MPa and had elongation of 25 %.

Figure 3-33. Schematic of long rod projectile used for experiment.

The projectile was launched in a projectile package shown in Figure 3-34. The projectile package consisted of 4-piece discarding sabot, pusher base, pusher and projectile. The 4-piece sabot guided the projectile during the acceleration within the launch tube. The

sabots would separate from the projectile upon exiting the launch tube. The launch mechanism of the projectile is a push system, whereby the projectile was accelerated by the pushing force exerted by the pusher from the rear of the projectile. A metallic base was placed in between the pusher and the projectile to prevent yielding of pusher during launch. The sabot separation is shown in Figure 3-35, where the sabot separation was symmetrical ensuring levelled projectile flight angle.

Figure 3-34. Image of parts of projectile package and projectile package assembled together.

Figure 3-35. Image of sabot separating from projectile captured by high speed camera.

3.2.3 Test Target Fabrication

There were two types of target used in the ballistic experiments. The first type of target was a monolithic steel block, while the second type of target was a ceramic armour module.

The monolithic steel block was made of AISI 4340 steel. It was a series of high strength steel with yield strength about 750 MPa. The dimensions of the target are shown in Figure 3-36. The target was used for DOP test, where the penetration depth of the projectile into monolithic steel block at a specific velocity was obtained. The dimensions were based on the work by Rosenberg and Dekel [17] and Littlefield et al. [18] which suggest the target dimensions should be at least double of the depth of penetration and 15 times the projectile diameter to remove any influence by the boundary of the target.

Figure 3-36. Dimension of test block for DOP test.

The ceramic armour module had a configuration shown in Figure 3-37. The primary components of the ceramic armour module were (1) cover plate, (2) ceramic (3) adhesive and (4) back plate. The thicknesses of the cover plate, ceramic, adhesive and back plate were 5 mm, 20 mm, 0.13 mm and 10 mm respectively.

Figure 3-37. Sectioned view of a ceramic armour module used for experimental testing.

The cover plate and back plate are made of AISI 4340 steel, the material was heat treated to the required hardness, the hardness used are specified in the relevant sections. For the ceramics, SiC from 3M Technical Ceramics, Germany, was used. The grades used are specified in the relevant sections.

The first step of assembly was sandblasting of ceramic tile and backing to improve adhesion. Both parts were sandblasted at grit 90, with average surface roughness of 145 microns. The surfaces were cleaned using acetone and blew dried using an air gun.

The next step was the preparation of the adhesive. The adhesive Loctite EA9309.3NA was used to bond the ceramic and backing plate. The adhesive was a two-part paste adhesive, where part A and part B were mixed with a weight ratio of 100 : 22. The mixing process was carried out using a planetary mixer, Kakuhunter SK-300 SV, by Shashin Kagaku Pte Ltd, Japan. It was a revolution-rotation mixer with degassing ability. The mixer was used to produce a homogeneous adhesive with minimal trapped air bubble to reduce the defect in the adhesive layer. The revolution speed was set at 1700 rpm while the rotation speed was set at 1160 rpm. The chamber pressure was drawn down to 0.001 bar and mixed for 3 mins.

A hydraulic press was used to apply a 0.5 kN load to press the adhesive to its minimum thickness of 0.13 mm as seen in Figure 3-38. The module was then secured with 8x M8 screws at the edge of the module. The load was held for 12 hours. The adhesive was then cure in an oven at 82 °C for 3 hours and cooled to room temperature overnight to achieve the adhesive maximum strength for testing.

Figure 3-38. Hydraulic press to apply 1 kN of load on ceramic armour module to achieve minimum thickness for adhesive.

3.2.4 Ballistic Performance

To study establish the correlation between ceramic armour hardness/toughness and its ballistic performance, the ballistic performance must be assessed. This was done by establishing the reference DOP into infinite steel block of AISI 4340. A series of DOP test was conducted at velocity ranging between 1000 m/s to 1400 m/s. The target was sectioned along the symmetrical plane for the maximum penetration depth to be measured.

An illustration of the DOP is shown in Figure 3-39 and DOP was measured using the following equation,

$$\text{DOP} = t_b - t_r \quad \text{Equation 3-8}$$

where t_b and t_r are the block thickness and the residual thickness of the reference block respectively.

Figure 3-39. Illustration of the DOP measurement [19].

All the test results are listed in Table 3-1. The results are plotted in Figure 3-40 and a linear best fit line was drawn to fit the data. The best fit line showed good fitting with the data with R^2 of 0.936.

Table 3-1. Results of measured DOP from different impact velocities.

Velocity (m/s)	1094	1190	1263	1268	1307	1338
DOP (mm)	46.0	62.5	66.6	65.1	68.7	75.9

Figure 3-40. Plot of DOP against velocity with best fit line.

The equation of the best fit line is,

$$DOP = 0.1091v - 71.52$$

Equation 3-9

where v is the impact velocity in m/s and DOP is the depth of penetration in mm.

The two most well accepted standards for measurement of ballistic performance are V_{50} and mass efficiency E_m . V_{50} was significantly costlier as it required at least 6 times more experiments than E_m to give meaningful data. On top of that V_{50} does not normalise weight of armour module, which is an important factor for assessment. With each experiment costing a few thousand dollars, E_m , being the more efficient and comprehensive indicator, was chosen over V_{50} as the method of assessment for ballistic performance.

E_m accounted for the differences in density and impact velocity to give a normalised value of comparison between modules. The E_m equation is,

$$E_m = \frac{AD_{ref}}{AD_{armour} + AD_{res}} \quad \text{Equation 3-10}$$

where AD_{ref} , AD_{armour} and AD_{res} represent the AD of AISI steel reference, ceramic armour and residual penetration into witness block respectively.

3.2.5 Materials

The materials used for the ceramic armour modules consisted of metal and ceramic. This section lists out all the materials used, their role within a ceramic armour and their material properties.

3.2.5.1 Ceramics

The primary material in a ceramic armour is the ceramic. There are few common ceramics which are used in ceramic armour such as Al_2O_3 , SiC and B_4C . In the experiments conducted, SiC was chosen to be the studied ceramic. SiC was chosen as it has the best performance for the usage of protection against long rod projectile at impact velocity at 1200 m/s. SiC had shown better performance over Al_2O_3 due to its ability to have dwell during the penetration process [20]. While B_4C faced amorphization problem when impacted by projectile above 800 m/s, limiting its use to below 1000 m/s [21], [22]. In the study, the author seeks to study the correlation between the material properties (hardness/toughness) and the ballistic performance of ceramic armour. Therefore, the ceramic chosen had to be of high quality while with almost similar properties and having slight differences that can be reflected in the ceramic armour performance. In the experiments, the ceramics were purchased from 3M Technical Ceramics, Germany, formally known as ESK.

The ceramic that were selected from their products for the experiments are SiC Grade F, Grade F+. Grade T and Grade T+. The material properties of the tiles given by the suppliers are listed in Table 3-2.

The difference with the F series and T series was that T series had YAG inclusion, which formed secondary phases at the SiC boundary, changing the fracture mechanism from transgranular to intergranular fracture [23]. This created a tougher ceramic with high fracture toughness of $6 \text{ MPa}\cdot\text{m}^{1/2}$ but lower hardness of 22 GPa. The main difference between the non-plus grade and the plus grade tiles was that plus tile underwent an additional step of post-HIP treatment, further densifying the ceramic and improved flexural strength.

Table 3-2. Material properties of various grade of SiC [24].

Properties	Grade F	Grade F+	Grade T	Grade T+
Microstructure	40μm		2μm	
Phase Composition	α -SiC	α -SiC	α -SiC, YAG	α -SiC, YAG
Density (g/cm ³)	> 3.15	> 3.18	> 3.21	> 3.24
Porosity (%)	< 2.0	< 1.0	< 1.0	< 1.0
Mean Grain Size (μm)	< 5	< 5	< 2	< 2
Vickers Hardness (GPa)	24.5	24.5	22.5	22.5
Young's Modulus (GPa)	430	430	420	430
Flexural Strength (MPa)	400	510	550	650
Compressive Strength (MPa)	> 2500	> 2500	>2500	>2500
Fracture Toughness (MPa.m ^{1/2})	4.0	4.0	6.0	6.0

3.2.5.2 Steel

AISI 4340 steel was used for the experiments. AISI 4340 is a nickel-chromium-molybdenum alloy steel. It is well known for high strength and toughness. The primary reason for choosing this material was its heat-treatability to require hardness. The specific conditions of heat treatment, i.e. heating temperature, holding time, quenching rate and etc were not known due to it being trade secret. The mechanical properties range selected were 4340 type U, Y and Z. The properties range are listed in Table 3-3.

Table 3-3. Material properties of various type of AISI 4340 [25].

4340 Type		U	Y	Z
UTS (MPa)	Min	930	1230	1550
	Max	1080	1380	-
Yield Stress 0.2% (MPa)	Min	740	1080	1125
Elongation %	Min	12	10	5
Hardness	Min	28	39	47
	Max	36	46	-

3.3 Hydrocode Simulation

For the hydrocode simulation, the solver used was LS-Dyna version 8.0 by LSTC, USA. It was a multi-purpose finite element programme for simulation of various real-world problems. For this work, explicit analysis was used. The pre-post processor used was LS-Prepost, a platform where the model building, and post simulation analysis were carried out.

3.3.1 Simulation Model

For the model building, FEM and SPH were used for the numerical analysis. FEM was used for the ceramic armour components while SPH was used for the projectile component as seen in Figure 3-41. As for ceramic, both FEM and SPH were used. The keyword DEFINE_ADAPTIVE_SOLID_TO_SPH was used to map each FEM element to a SPH node accordingly. When the FEM element reaches its deletion criteria, the stress information was transferred to SPH node to carry on the simulation. This method was used to overcome the problem of ceramic element deletion, where the deletion of element would result in a loss of confinement pressure of the neighbouring elements. As ceramic strength is pressure dependant, the loss of confinement pressure would reduce the ceramic performance, reducing the accuracy of the simulation. If the deletion criterion was remove, the highly-distorted element would result in instability of simulation results that might

result in premature termination. Therefore, by using this keyword, the confinement pressure within the ceramic was maintained while dealing with distorted element.

Figure 3-41. Image of model used for simulation of ballistic experiment.

The mesh size of the FEM and SPH were set at 0.8 mm and 0.4 mm respectively. The SPH size was selected to ensure the tip of the projectile had 4 nodes. The mesh size of the FEM was determined after a series of simulation with different mesh size. Different mesh sizes were tested, and mesh size below 1 mm was observed to not be influenced by the mesh size effect. The final mesh size was selected to optimize between accuracy and computation time. The model used in the simulation was half model, assuming the problem was a symmetrical problem. The typical model had 1 million FEM elements and 1 million SPH particles and takes a running time of 8 hours to complete simulation, using 8 cores.

The contacts between the parts used keyword,

CONTACT_ERODING_NODES_TO_SURFACE/SURFACE_TO_SURFACE,

depending on SPH-FEM or FEM-FEM contact. This contact was used as the elements were subjected to erosion as part of the material failure criteria. This type of contact algorithm contain logic which updates the new contact surface as the exterior surfaces were being deleted.

The adhesive between ceramic and backing was not modelled as its thickness of 0.13 mm was smaller than the element size, instead it was represented in the simulation using a tiebreak contact. The keyword used was,

CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK,

where the surface nodes between ceramic and backing were joined together. When the stress at the interface reached the input value of 200 MPa of normal stress, the joint surface would be separated. This simulated the de-bonding of the adhesive during penetration process.

3.3.2 Materials Model

The detailed description of the material model is listed under Section 2.7 in the literature review chapter. In this section, the material parameters used for the simulation are listed.

3.3.2.1 JC Model

JC model described the material behaviour of tungsten alloy and AISI 4340 in this study. The AISI 4340 steel material parameters were obtained from the work done by Deniz and Yildirim [26]. Their work established an empirical equation for the material parameters and hardness of the steel. The equations are as follow,

$$A = \exp(0.0355 \cdot \text{HRC} + 5.5312) \text{ [MPa]} \quad \text{Equation 3-11}$$

$$B = 0.6339 \cdot A \text{ [MPa]} \quad \text{Equation 3-12}$$

$$n = 0.0172 \cdot \text{HRC} - 0.4144 \quad \text{Equation 3-13}$$

$$C = -0.0001 \cdot \text{HRC} + 0.011 \quad \text{Equation 3-14}$$

The last coefficient m , the temperature exponent is fixed at 1.03 across all hardness, as it was assumed softening effect by temperature is not affected by hardness.

The material parameters for the tungsten alloy were obtained experimentally. All the parameters for JC model and material properties of various hardness AISI 4340 and tungsten alloy are listed in Table 3-4.

Table 3-4. JC parameters for different hardness steel and tungsten alloy.

JC Model Strength Parameters	HRC 30 ^[26]	HRC 40 ^[26]	HRC 50 ^[26]	WHA
Yield Strength, A (MPa)	719	1026	1463	697
Hardening Coefficient, B (MPa)	456	650	927	1160
Strain Hardening Exponent, n	0.093	0.265	0.426	0.626
Strain Rate Constant, c	0.008	0.007	0.006	0.056
Softening Exponent, m	1.03	1.03	1.03	1.00
Material Properties				
Density (g/cm ³)	7.85	7.85	7.85	17.6
Young's Modulus (GPa)	201	201	201	320
Shear Modulus (GPa)	78	78	78	160
Poisson's Ratio	0.29	0.29	0.29	0.29
Melting Temperature (K)	1723	1723	1723	1730
Specific Heat (J/kg.K)	477	477	477	134

3.3.2.2 SiC

Table 3-5. Material parameters of JH-1 model for different grade of SiC.

SiC Grade	Grade T	Grade T+	Grade F	Grade F+ ^[27]
Strength Parameters: JH-1 Model				
Intact Strength Constant, S_1 (MPa)	6000	6082	6692	7100
Intact Strength Constant, P_1 (MPa)	2500	2500	2500	2500
Intact Strength Constant, S_2 (MPa)	10300	10450	11500	12200
Intact Strength Constant, P_2 (MPa)	10000	10000	10000	10000
Strain Rate Coefficient, C	0.01	0.01	0.01	0.01
Tensile Strength, T (MPa)	750	750	750	750
Failure Parameters: JH-1 Model				
Max Fracture Strength, $S_{\max}^f$ (MPa)	1300	1300	1300	1300
Failed Strength Constant, α	0.4	0.4	0.4	0.4
Damage Constant, $\epsilon_{\max}^f$	0.8	0.8	0.8	0.8
Damage Constant, ϕ	0.8	0.8	0.8	0.8
Damage Constant, P_3 (MPa)	99750	99750	99750	99750

The material parameters of SiC are listed in Table 3-5. The strength model parameters of Grade F+ SiC was obtained from the literature [27]. The damage constant ϕ was obtained through varying ϕ until simulation results matched the experimental results, this was done according to the literature [27]. The remaining grade of ceramic strength parameters were scaled according to their measured hardness. The validity of the results is discussed in Chapter 5.

3.3.3 Dwell Determination

Dwell is the centre piece of the theory of the work conducted, an accurate determination of dwell time is of great importance. The dwell time was predicted through simulation. The start of dwell was determined to be the first instance which the projectile impact the surface of the ceramic tile and the termination of dwell was defined as the first

frame which the ceramic tile was first eroded as shown in Figure 3-42(a). The tile erosion was defined by the conversion from FEM to SPH particles as seen in Figure 3-42(b), where the converted SPH particles are in green.

Figure 3-42. (a) Starting of dwell and (b) termination of dwell.

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Chapter 4 *

Effect of Hardness/Toughness of Cover Plate

In this chapter, the influence of cover plate hardness and fracture toughness on ballistic performance of ceramic armour studied through experimentations and simulations. From the ballistic experimental results, it was observed that hardness had no influence on the ballistic performance of ceramic armour, while decreased fracture toughness reduced ballistic performance of ceramic armour. The mechanism which the cover plate influences the ballistic performance was studied using simulations. The cover plate has two critical roles; (1) blunting of cover plate and (2) acting as a shock attenuator. The two roles are independent of cover plate hardness; thus, hardness has no influence on ballistic performance of ceramic armour. Reduced fracture toughness results in loss of confinement pressure during dwell phase which leads to premature dwell termination and thus reduced ballistic performance of ceramic armour.

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4.1 Introduction

Cover plate is an essential part in a ceramic armour. There is a lack of publication in research work which shed light on the role of cover plate in a ceramic armour. Espinosa et al. [1] performed impact recovery experiments on confined multi-layered ceramic targets to identify materials and structural design issues in interface defeat of long rod WHA penetrators. The experimental results showed that complete penetration occurred when using the steel cover of HRC 35 whereas complete interface defeat while using steel cover of HRC 53. Hence, the authors concluded that hardness of HRC 53 and above was required for interface defeat. Behner et al. investigated the dwell capability of single ceramic tiles of limited thickness for protection against tungsten-heavy-alloy rod penetrators [2–3], the process of dwell was captured using high speed camera and Flash X-ray. It was concluded that a copper cover plate would raise the dwell velocity, i.e. the impact velocity which dwell could occur, from 1200 m/s to around 1660 m/s, demonstrating that cover plate improved ballistic performance through dwell.

However, 30 – 50 mm thick cover plates and bulky jigs using welding and shrink-fitting was applied in the armour targets in Espinosa et al. [1] research work, while copper cover (copper had higher density than steel) coupled with an 80 mm thick backing of RHA was used in Behner et al. studies [2–3]. These configurations using thick cover or high density material are not recommended for practical applications, where lightweight design is of high priority.

This chapter aims to study the influence of cover plate hardness and fracture toughness on ballistic performance of ceramic armour with emphasis places on defeat mechanism when using a lightweight cover. Consequently, 5 mm thick steel cover plates with different hardness and fracture toughness are investigated.

4.2 Experiment and Armour Module

Single tile ceramic armour designed for the study is shown in Figure 3-37 and the test matrix is shown in Table 4-1. The initial design of the module is having backing plate material and ceramic fixed as AISI 4340 steel heat treated to HRC 30 and Grade F+ SiC respectively while the cover plate material consisted of AISI 4340 steel heat treated to HRC 30, HRC 40 and HRC 50. However, after conducting test set 01 – 03, it was decided that the study was repeated with Grade T+ SiC in test set 04 – 06 to improve on the confidence of the results observed for test set 01 – 03.

The armour modules fabricated were tested on the two-stage light gas launcher in the MJHSDL. A detailed description of the fabrication process of the experimental setup and target fabrication is listed in Section 3.2.2 and Section 3.2.3 respectively. After testing, the witness block was sectioned along the penetration line so that the residual penetration was measured to calculate the mass efficiency, E_m ; detailed explanation of mass efficiency is listed in Section 3.2.4.

Table 4-1. Test matrix for single tile module for study of ceramic hardness and fracture toughness on ballistic performance.

Test Set	Cover Plate	SiC Grade	Backing Plate
01	AISI HRC 30	Grade F+	AISI HRC 30
02	AISI HRC 40	Grade F+	AISI HRC 30
03	AISI HRC 50	Grade F+	AISI HRC 30
04	AISI HRC 30	Grade T+	AISI HRC 30
05	AISI HRC 40	Grade T+	AISI HRC 30
06	AISI HRC 50	Grade T+	AISI HRC 30

4.3 Experimental Results

Three hardnesses for cover plate material were selected for the study on cover plate influence, HRC 30, 40 and 50. Steel hardness and fracture toughness were measured and

lists in Table 4-2. Six measurements were taken for each specimen for hardness while one measurement was taken for each specimen for fracture toughness due to the cost of the tests. Measurement of hardness and fracture toughness are presented in Section 3.1.1 and Section 3.1.3 respectively. From Table 4.2, the hardness ranges from HRC 29 to HRC 50 while the fracture toughness K_{Ic} ranges from $52 \text{ MPa}\cdot\text{m}^{1/2}$ to $125 \text{ MPa}\cdot\text{m}^{1/2}$. As hardness increases, fracture toughness decreases.

Table 4-2 Measurement of hardness and fracture toughness of various hardness AISI 4340.

Steel	HRC 30	HRC 40	HRC 50
Hardness (HRC)	29.3 ± 0.7	40.4 ± 0.6	50.0 ± 0.3
Fracture Toughness ($\text{MPa}\cdot\text{m}^{1/2}$)	125.43	117.71	51.81

4.3.1 Grade F+ Tiles Results

The results of measured residual depth of penetration and the calculated mass efficiency are provided in Table 4-3. Three tests were carried out for each cover plate hardness. The experimental results are plotted in Figure 4-1. The test results showed that when the cover plate hardness increased from HRC 30 to HRC 40, (fracture toughness decreased slightly from $125 \text{ MPa}\cdot\text{m}^{1/2}$ to $118 \text{ MPa}\cdot\text{m}^{1/2}$), the obtained mass efficiency remained at 1.6. Therefore, it appears that the ballistic performance is independent of the hardness and fracture toughness of the cover plate in the test ranges. However, when the hardness increased from HRC 40 to HRC 50, (fracture toughness decreased from $118 \text{ MPa}\cdot\text{m}^{1/2}$ to $52 \text{ MPa}\cdot\text{m}^{1/2}$) the mass efficiency decreased from 1.60 to 1.55. The slight decrease in mass efficiency is not conclusive due to the spread of the data. Therefore, additional experiments were conducted using Grade T+ tiles.

Table 4-3. Experimental results of different hardness cover plate with Grade F+ tiles.

S/N	Hardness (HRC)	Velocity (m/s)	Ref DOP (mm)	Res DOP (mm)	E_m	Average
FC30-1	30	1195	58.9	14.0	1.59	1.59
FC30-2	30	1269	66.9	16.3	1.70	
FC30-3	30	1239	63.7	19.7	1.49	
FC40-1	40	1247	64.5	15.9	1.65	1.60
FC40-2	40	1247	64.5	18.3	1.56	
FC40-3	40	1237	63.4	16.9	1.59	
FC50-1	50	1233	63.0	15.9	1.62	1.55
FC50-2	50	1293	69.6	27.5	1.37	
FC50-3	50	1220	61.6	12.6	1.72

Figure 4-1. Plot of mass efficiency against cover plate hardness using Grade F+ tiles.

4.3.2 Grade T+ tiles Results

The experimental results conducted with Grade T+ SiC is shown in Table 4-4. The trend in the experimental results is consistent with the trend seen in Grade F+. The mass efficiency remained consistent at 1.53 when the cover plate hardness increased from HRC

30 to HRC 40 (fracture toughness slight decreased from $125 \text{ MPa}\cdot\text{m}^{1/2}$ to $118 \text{ MPa}\cdot\text{m}^{1/2}$). When the when the hardness increased from HRC 40 to HRC 50, (fracture toughness decreased from $118 \text{ MPa}\cdot\text{m}^{1/2}$ to $52 \text{ MPa}\cdot\text{m}^{1/2}$) mass efficiency decreased from 1.53 to 1.41. With a smaller standard deviation for Grade T+ (0.06 as compared to 0.15 for Grade F+) it is confirmed that cover plate with hardness of HRC 50 has poorer ballistic performance. By plotting the mass efficiency against cover plate fracture toughness in Figure 4-2, it is concluded that decreased fracture toughness results in reduction in ballistic performance of ceramic armour.

Table 4-4. Experimental results of different hardness cover plate with Grade T+ tiles.

S/N	Hardness (HRC)	Velocity (m/s)	Ref DOP (mm)	Res DOP (mm)	E_m	Average E_m
TC30-1	30	1258	65.7	19.7	1.53	1.52
TC30-2	30	1259	65.8	20.2	1.52	
TC30-3	30	1204	59.8	16.8	1.50	
TC40-1	40	1257	65.6	20.7	1.50	1.53
TC40-2	40	1246	64.4	18.2	1.56	
TC50-1	50	1247	64.5	20.7	1.47	1.41
TC50-2	50	1247	64.5	24.8	1.34

Figure 4-2. Plot of mass efficiency against cover plate fracture toughness using Grade T+ tiles.

4.4 Simulation and Defeat Mechanism

Hydrocode simulation of experiment was carried out to interpret the test results obtained in above section. The interaction between the long rod projectile and the armour module target was studied. This simulation focuses on the initial phase of penetration, i.e. first 10 μ s, when the projectile is penetrating the cover plate and impacting the ceramic tile. A comparison is made between a ceramic armour module with and without cover plate. The impact pressure at the surface of the ceramic tiles were compared. The stress of the Element 1 at the middle of the tile seen in Figure 4-3 was read off the simulation data. The stresses were read off at 0.1 μ s interval.

Figure 4-3. Simulation model indicating the element which Von Mises stress was read off.

A detailed description of the simulation model and element settings is provided in Section 3.3.1. The materials models for the materials used in the armour module are provided in Section 3.3.2.

4.4.1 Shock Attenuation

Figure 4-4 shows a plot of the impact pressure on ceramic surface against time. From the graph, it appears that without cover plate, the normal stress experiences by ceramic reaches around 15 GPa, which is above the Hugoniot Elastic Limit (HEL) of SiC (11.7 GPa reported in [4–5],) resulting in plastic deformation of the ceramic tile. Ceramic is extremely brittle, fracturing when experiencing plastic deformation, approximately 8 % for SiC [6]. With the use of a cover plate, the peak pressure is reduced to 6 GPa, which is much lower than HEL of SiC.

Besides the peak pressure, a shock is generated during the impact in the case of no cover plate, where the pressure on ceramic face increases from 0 to 15 GPa in 0.2 μ s. Short loading time of the impact stress easily causes localized damage in the ceramics around the tip of the impacting long rod, preventing the establishment of dwell. However, with the use of cover plate, the pressure increases in a smoother manner, the pressure increases from 0 to 6 GPa over a period of 7 μ s, which prevents damage in the ceramics around the tip of the impacting long rod. This results in dwell establishing for ceramic armour with cover plate.

A comparison between the simulation results of no cover plate and with a cover plate is plotted in Figure 4-5, where projectile penetrates the ceramic immediately on contact in the case of no cover plate (Figure 4-5a) while dwell is still ongoing even after $30\mu\text{s}$ after impact in the case of using a cover plate. Therefore, one of the roles of a cover plate is to attenuate the initial shock load applied to the SiC tiles.

Figure 4-4. Plot of impact pressure on ceramic surface against time [7].

Figure 4-5. Projectile penetration status into ceramic armour at 30 μ s after impact (a) without cover plate (penetration into ceramic) and (b) with cover plate (dwell on surface).

4.4.2 Blunting of the projectile

The second mechanism of the cover plate is the blunting of projectile tip. Typical projectile nose is conical for better penetration capability [8–9]. The cover plate blunts the conical nose, increasing cross-sectional loading area and reducing the peak pressure as seen in Figure 4-4. The diameter of projectile nose increases from 1.5 mm to 3.6 mm when it impacts the ceramic surface at 10 μ s as seen in Figure 4-6. These two mechanisms are the ways which the cover plate contributes in a ceramic armour system.

Figure 4-6. Projectile nose profile at, (a) 0 μ s and (b) 10 μ s.

4.5 Discussion

4.5.1 Cover Plate Hardness

A plot comparing the impact pressure of various hardness cover plate is plotted in Figure 4-7. From the plot, no difference in the pressure profile is observed for the three hardness and peak pressure across different cover plate hardness for the initial 8 μ s, indicating that the impact pressure is independent of the cover plate hardness. The decrease pressure for HRC 50 will be explained in the later segment of this section.

Figure 4-7. Plot of impact pressure on ceramic surface for different cover plate hardness against time.

The cover plate hardness influence on its blunting capability are studied. The diameter of the projectile nose was tracked and measured during the penetration of cover plate for different cover plate. The results are plotted in Figure 4-8. The diameter of the projectile increased from 1.3 mm to 10 mm in 13 μ s for all cover plate hardnesses. There is no difference in the projectile nose diameter, regardless of the hardness value. As both mechanisms are not influenced by hardness of cover plate, therefore, ballistic performance of ceramic armour is independent of cover plate hardness.

The conclusion that this study reaches is different from the conclusion drawn by Espinosa et al. [1]. By comparison, the design used by Espinosa et al. had a 25 mm cover plate which was 5 times the thickness of the cover plate thickness used in this study. The role of the cover plate in the design acts as a confinement, thus hardness increase would provide a better confinement which is different from thin cover plate. For thin cover plate, the increased cover plate hardness is unable to provide difference in the degree of confinement as seen in Figure 4-7 where the impact pressure is similar across the hardness for first 7 μ s. Noting the difference, the conclusion drawn in this study is limited to thin cover plate, i.e. thickness less than projectile diameter.

Figure 4-8. Diameter of projectile nose for different hardness cover plate against time.

4.5.2 Cover Plate Fracture Toughness

Reduced cover plate fracture toughness is observed to reduce ballistic performance of ceramic armour. The additional role which the cover plate plays is to provide top confinement pressure during penetration process. The bulging of the cover plate is shown in Figure 4-9, confining the eroded projectile material and maintaining the pressure on the

surface of the ceramic. As ceramic strength is pressure dependant, the build-up pressure will strengthen the ceramic.

Figure 4-9. Confinement of eroded projectile material leading to bulging of cover plate (blue box).

The condition of the cover plates after the test is compared in Figure 4-10. It is observed that the cover plate with hardness of HRC 30 remains intact with only a hole at the impact point. The diameter of the hole was 8.3 mm which is same as the diameter of the projectile. This provides good confinement during the dwell phase, limiting most material within the cover plate as seen in Figure 4-11, where more than half of the projectile had been eroded while minimal amount of material was ejected. For the cover plate with hardness of HRC 50, the hole diameter was 14.3 mm and had fractured into 4 pieces. It is predicted that cover plate fracture will result in loss of confinement pressure.

Figure 4-10. Picture of cover plate with HRC 30 and 50 after experiment. (a) The material around the impact location is intact for HRC 30 hardness cover plate and (b) cracks originated from impact location are observed for the HRC 50 cover plate.

Figure 4-11. High speed image of target during penetration by projectile where eroded material is boxed in red. Minimal eroded material is ejected when more than half of projectile length penetrates the ceramic armour module.

Analysis of the impact pressure on the ceramic surface was done using simulation, a sudden drop of confinement pressure is observed for HRC 50 hardness cover plate as

seen in Figure 4-12. Looking at the section mark with a red box, there are two factors which contribute to poorer ballistic performance, (1) the loss of confinement pressure, the pressure drop from 5 GPa to 0.5 GPa in an instant, and (2) a shock where the pressure increased to 6 GPa within 0.3 μ s, similar to the shock seen in Figure 4-4 for the case without a cover plate. The loss of confinement pressure reduces the strength of the ceramic while the shock damages the ceramic, leading to termination of dwell. The early termination of dwell will negatively impact the ballistic performance of ceramic armour.

Figure 4-12. A plot of impact pressure on ceramic surface of different cover plate hardness against time.

4.6 Conclusion

Based on the experimental and simulation work conducted above, hardness of cover plate did not influence the ballistic performance of ceramic armour while reducing fracture toughness reduces the ballistic performance within the test conditions. This is due to the two primary defeat mechanisms of the cover plate: (1) blunting of projectile and (2) shock attenuation not affected by hardness of cover plate. Low fracture toughness results in loss of confinement pressure during the dwell phase, resulting in premature dwell termination and damage of ceramic tiles. This leads to reduce ballistic performance.

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Chapter 5 *

Effect of Hardness/Toughness of Ceramics

In this chapter, the influence of ceramic hardness and fracture toughness on ceramics armour ballistic performance were studied through experimentations and simulations. From the ballistic experiment results, increased ceramic hardness is observed to improve ballistic performance of ceramic armour, while fracture toughness did not affect the ballistic performance in terms of mass efficiency. However, fracture toughness has great influence on the integrity of the surrounding ceramics after impact. To model the effect ceramic hardness, ceramic strength parameters, $S1$ and $S2$, of JH-1 model are assumed to be proportional to the hardness of ceramics. The simulation results show that this method of scaling JH-1 strength parameters to ceramic hardness reproduces the experimental results with good accuracy. Simulations reveal that increased ceramic hardness improved ballistic performance by extending dwell time. When ceramic fracture toughness increased from $2.89 \text{ MPa}\cdot\text{m}^{1/2}$ to $6.99 \text{ MPa}\cdot\text{m}^{1/2}$, damage by tensile waves is suppressed, thus significantly reduce the damage radius.

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5.1 Introduction

Two of the important material properties that are used to guide the selection of ceramics for lightweight armour are hardness and fracture toughness [1–2]. Improving both the hardness and toughness of SiC simultaneously is a challenging task, consequently, trade-off between hardness and toughness always occurs [3]. Balancing between ceramic hardness and toughness has always been a critical task to ceramic armour designers.

Flinders and Ray et al. [4–5] conducted DOP tests where 7.62 x 51 mm simulants were shot at a velocity of 907 m/s into 6.35 mm thick SiC ceramic tiles backed with 130 mm thick Al5083 block. The experimental results indicated that ballistic performance of ceramic armour module increased with increasing ceramic hardness while increased ceramic fracture toughness did not appear to improve armour performance. A recent study conducted by Hallam et al. [6], 7.62 mm projectile was used in experiment to correlate hardness of ceramic against its V_{50} ballistic performance. They concluded that the ceramic hardness and its ability to sustain dwell improved ceramic ballistic performance and damage propagation had a smaller role to play in comparison.

These reported studies correlated mechanical properties such as hardness and fracture toughness with ballistic performance focussed on low level threat, i.e. small calibre projectiles with impact velocity below 1000 m/s. Moreover, defeat mechanisms for ceramic hardness and fracture toughness against projectile impact had not been identified. There is a lack of literature reporting correlation between mechanical property of ceramic hardness and fracture toughness and ballistic performance subjected to high level threat, i.e. long rod projectile with impact velocity above 1000 m/s. Armour's interaction with long rod projectile is known to be different from small calibre projectile [6-8]. Therefore, this chapter aims to identify the effect of ceramic hardness and fracture toughness on ballistic performance of a ceramic armour module as well as the mechanisms which defeat long rod projectile at impact velocity above 1000 m/s.

5.2 Armour modules and test matrix

In the study of ceramic hardness and fracture toughness, two different types of ceramic armour modules were designed: (1) the single-tile ceramic armour module and (2) the multiple-tile ceramic armour module. The design of the single tile ceramic armour module is shown in Figure 3-37. The cover plate and backing plate materials were fixed as AISI 4340 steel heat treated to HRC 30. The following ceramic grades were chosen: Grade T, Grade T+, Grade F, and Grade F+ SiC from 3M Technical Ceramics, Germany. Detailed description of ceramic armour module fabrication is found in Section 3.2.3 and the experiment setup is found in Section 3.2.4. The test matrix is shown in Table 5-1.

Table 5-1. Test matrix for single tile module for study of ceramic hardness and fracture toughness on ballistic performance.

Test Set	Cover Plate	SiC Grade	Backing Plate
01	AISI HRC 30	Grade T	AISI HRC 30
02	AISI HRC 30	Grade T+	AISI HRC 30
03	AISI HRC 30	Grade F	AISI HRC 30
04	AISI HRC 30	Grade F+	AISI HRC 30

The other amour module was the multiple-tile ceramic armour module. The design of the module is shown in Figure 5-1. It consisted of the following components: (1) cover plate, (2) 6 pieces of ceramics arranged in a row, (3) adhesive, (4) 25 mm lateral confinement and (5) backing plate. The thickness of the cover plate, ceramic, adhesive, lateral confinement and back plate were 5 mm, 20 mm, 0.13 mm, 20 mm and 13 mm, respectively. The fabrication process was identical to the process mentioned in Section 3.2.3.

The test matrix of the module is listed in Table 5-2. The backing plate and cover plate was changed to Hardox 400 from SSAB, Sweden. The comparison is done between SiC of Grade T+ ($K_{Ic} = 6.99 \text{ MPa.m}^{1/2}$) and Grade F+ ($K_{Ic} = 2.89 \text{ MPa.m}^{1/2}$). The experimental setup is shown in Figure 5-2. The module was placed vertically in the target

chamber with the top tile targeted and the module secured to the chamber using steel wire to prevent secondary damage caused by impact against target chamber.

Figure 5-1. Sectioned view of 6-tile module.

Table 5-2. Test matrix for 6-tile module.

Test Set	Cover Plate	Ceramic Grade	Confinement	Back Plate
01	Hardox 400	Grade T+	Mild Steel	Hardox 400
02	Hardox 400	Grade F+	Mild Steel	Hardox 400

Figure 5-2. Multiple tiles module used for obtaining damage radius of Grade T+ and F+ tiles where (a) module without cover plate and (b) target setup within the target chamber.

5.3 Experimental Results

The measured mechanical properties of the 4 different grades of SiC ceramics are listed in Table 5-3. The results listed are an average of twelve readings from two tiles for each grade; 10 kgf of load was used. The details of hardness and toughness measurements are mentioned in Section 3.1.1. As shown in Table 5-3, F series tiles has high hardness and low fracture toughness; on the other hand, T series tiles has high fracture toughness and low hardness.

Table 5-3. Measured mechanical properties of four grades of SiC tiles from 3M Technical ceramics.

Ceramic	Grade F	Grade F+	Grade T	Grade T+
Hardness (HV)	23.1±0.9	24.4±0.9	20.6±0.3	20.9±0.8
Toughness (MPa.m ^{1/2})	2.84±0.20	2.89±0.23	5.79±0.49	6.99±0.78

5.3.1 Single Tile Modules

After testing, the witness blocks were sectioned along the penetration line to measure the residual penetration according to the method listed in Section 3.2.4, which were then used to calculate the mass efficiency based on Equation 3-7. The experimental results for the single tile modules are listed in Table 5-4.

Table 5-4. Experimental results of 4 grades of SiC in single tile armour module test.

Ceramic	S/N	Velocity (m/s)	DOP (mm)	E_m	Average E_m
Grade T	T1	1220	16.5	1.55	1.53
	T2	1261	24.0	1.40	
	T3	1228	14.7	1.65	
Grade T+	T+1	1258	19.7	1.53	1.52
	T+2	1259	20.2	1.52	
	T+3	1204	16.8	1.50	
Grade F	F1	1265	17.6	1.63	1.62
	F2	1253	18.9	1.55	
	F3	1224	14.0	1.67	
Grade F+	F+1	1269	16.3	1.70	1.73
	F+2	1239	19.7	1.49	
	F+3	1231	6.6	2.11	
	F+4	1195	14.0	1.59	
	F+5	1256	10.9	1.93	
	F+6	1236	16.7	1.59	

The test results are plotted against hardness, a linear relation is observed as seen in Figure 5-3. Higher hardness is observed to correlate with better ballistic performance of higher mass efficiency in SiC, where the mass efficiency (E_m) increases from 1.52 to 1.73 (an increment of 13.2 %) as Vickers hardness increases from 20.6 GPa to 24.4 GPa (an increment of 18.4 %). However, the ballistic performance is not influenced by fracture toughness as seen from Figure 5-4.

This conclusion is in agreement with Darin et al. [5]; although that work is based on 7.62 mm projectiles instead of the long rod projectiles used in this experiment and the hardness used is Knoop hardness instead of Vickers hardness.

Figure 5-3. Ceramic hardness plotted against mass efficiency of ceramics.

Figure 5-4. Ceramic fracture toughness against mass efficiency of ceramics.

5.3.2 Multiple-Tile Module

A total of two shots were conducted in the study using the multiple-tile module. Different from that of testing of single tile module, the primary objective of the experiments here was to understand the influence of fracture toughness on damage condition of neighbouring tiles. The damage radius was defined as the distance from impact point to the furthest point on the cracked tile.

Figure 5-5 shows an image of tested ceramic array. Grade T+ had a damage radius of 138 mm while Grade F+ had a damage radius of 420 mm. Although some cracks were observed in tile 4 of Grade T+ experiment as seen in Figure 5-6, it was not considered during the measurement of the damage radius. The reason being that the crack was caused by secondary damage, i.e. ceramic armour module impacting the target chamber after shot. The above conclusion was drawn from two pieces of evidences, (1) no damage was observed in tile 3 and (2) the crack was observed to originate from a point source from the edge of the tile indicated in Figure 5-6, suggesting the damage is caused by an impact at the location. Therefore, it was concluded that Grade T+ SiC tiles have better structural integrity than Grade F+ tiles after test.

Figure 5-5. Damage condition of neighbouring tiles of (a) Grade T+ and (b) Grade F+ ceramics after impact.

Figure 5-6. Enlarged image of tile 3 and 4 in Grade T+ experiment.

A further analysis of the ceramic fragments was conducted using SEM. The pictures of the fragments are seen in Figure 5-7. By comparing with the work done by Liu et al. [7], it appears that Grade T+ SiC is dominated by intergranular fracture, where multiple crack deflections are observed, a typical phenomenon for intergranular fracture. For Grade F+, the crack has little deflection, indicating it is dominated by transgranular fracture. The fracture mechanisms have resulted in the fracture toughness for the respective grade of SiC.

Figure 5-7. SEM images of fracture surface of ceramic fragments of (a) Grade T+ and (b) Grade F+ and SEM image of (c) intergranular crack and (d) transgranular crack from literature [7].

5.4 Simulation

Detailed explanation of the simulation model is listed in Section 3.3.1 while the material model is discussed in Section 3.3.2.

5.4.1 Simulation of ceramics with different hardness

The simulation was carried out using LS-Dyna explicit analysis, using two material models: Johnson-Cook (JC) model for the AISI 4340 steel and tungsten alloy, and Johnson-Holmquist-1 (JH-1) model for SiC.

The parameters of tungsten alloy and AISI 4340 were obtained through experiment and literature [8–9] respectively, as shown in Table 5-5.

Table 5-5. Material parameters for JC strength model of tungsten alloy and AISI 4340 steel.

Parameters	Tungsten Alloy ^[9]	HRC 30 ^[8]
A (MPa)	697	719
B (MPa)	1160	456
n	0.626	0.093
c	0.056	0.008
m	1.00	1.03

JH-1 model was applied for the SiC ceramic. The grade F+ parameters were obtained from literature [9]. The strength parameters S_1 and S_2 of the remaining grades of SiC were scaled proportionately against the measured hardness of the ceramics. The parameters are listed in Table 5-6. Figure 5-8 shows the pressure dependent strength of ceramics known as JH-1 model [10]. As seen in literature [11–12], S_1 and S_2 represent the strength of ceramic when a hydrostatic pressure of P_1 and P_2 was applied to the ceramic. The strength of ceramic is known to be closely related to the hardness of the ceramics. Hence it was assumed that S_1 and S_2 are proportional to hardness, whose validity was evaluated in simulations.

Figure 5-8. Plot of equivalent stress against pressure in ceramic describing the ceramic strength to pressure relationship in JH-1 model [10].

Table 5-6. JH-1 parameters of different grade of SiC.

	SiC Grade	Grade T	Grade T+	Grade F	Grade F+ ^[9]
Strength Parameters: JH-1 Model					
Intact Strength Constant, S_1 (MPa)		6000	6082	6692	7100
Intact Strength Constant, P_1 (MPa)		2500	2500	2500	2500
Intact Strength Constant, S_2 (MPa)		10300	10450	11500	12200
Intact Strength Constant, P_2 (MPa)		10000	10000	10000	10000
Strain Rate Coefficient, C		0.01	0.01	0.01	0.01
Tensile Strength, T (MPa)		750	750	750	750
Failure Parameters: JH-1 Model					
Max Fracture Strength, S_{max}^f (MPa)		1300	1300	1300	1300
Failed Strength Constant, α		0.4	0.4	0.4	0.4
Damage Constant, ϵ_{max}^f		0.8	0.8	0.8	0.8
Damage Constant, ϕ		0.008	0.008	0.008	0.008
Damage Constant, P_3 (MPa)		99750	99750	99750	99750

5.4.2 Single Tile Module

As the method of scaling of ceramic strength constant to ceramic hardness has not been done by any others before, therefore, the validity of the method must first be determined. Figure 5-9 shows a plot comparing the simulation results with experimental

results. The simulation results match the experimental results well. The maximum deviation from experimental average is mass efficiency of 0.06 (3.5%). Therefore, this method of scaling ceramic strength parameters to ceramic hardness is a valid method for high performance SiC.

Figure 5-9. Plot of mass efficiency against different grades of SiC for experimental and simulation results.

After establishing the validity of the hardness scaling method, the penetration process of ceramic armour was studied. As the primary mechanism of ceramic armour for long rod projectile is erosion, the erosion rate of ceramic armour is studied. The position of projectile tip of different ceramic is plotted against time in Figure 5-10. In Figure 5-10, the penetration phase is separated into three phases (1) penetration of cover plate, (2) dwelling on the surface of ceramic and (3) penetration in to ceramic. As seen from the plot, it is observed that the gradients of the three phases are similar across the ceramics, i.e. the erosion rates for all ceramics at a specific phase are the same. The main difference is the duration of dwell. The ceramics have different dwell termination time. Dwell being the most efficient projectile erosion phase; (erosion rate approximately projectile impact velocity). The dwell time is compared against the ceramic hardness in Figure 5-11. From the plot, the dwell time is observed to correlate to ceramic hardness. The dwell time

increases from 23 μs to 31 μs when the hardness of ceramics increases from 20.6 GPa to 24.4 GPa.

Figure 5-10. A plot of dwell time against ceramic hardness.

Figure 5-11. A plot of projectile tip displacement against time for 4 grades of SiC, 3 distinct phases are observed; (1) penetration of cover plate, (2) dwell and (3) penetration of ceramic.

Based on the experimental results, fracture toughness has negligible influence on the ballistic performance of ceramic armour. Through data provided in simulation, the projectile (mass = 96g and measured impact velocity = 1250 m/s) has a kinetic energy of 75 kJ, while the ceramic dissipates around 0.78 kJ of energy. The energy dissipates by fracture of ceramic is approximately 1 % of the projectile's kinetic energy. Therefore, there

is negligible influence by ceramic fracture toughness on ballistic performance of ceramic armour.

5.4.3 Multiple Tile Module

It is hypothesised that the neighbouring tiles are damaged by the stress wave generated by the projectile impact, therefore, to study the stress wave generated, the model shown in Figure 5-12 was built. The model was a full model, with 6 individual tiles model using FEM and the projectile with SPH. A gap of 0.1 mm was left between the tiles to represent adhesive in between tiles. The damage criterion of the ceramic tiles was removed allowing stress wave profile to be studied.

Figure 5-12. Top view of model used for multiple-tile module.

Figure 5-13 shows the stress propagation along the direction of tile row (x-axis) in the first 44 μs after impact. The impact at tile 1 created an initial compressive wave (blue box) in tile 2, propagating through the ceramics from left to right. The compressive stress wave reflects at the adhesive interface between ceramic tile 1 and 2, creating tensile stress wave (red box) as seen in 17 μs , 24 μs , 35 μs and 44 μs in Figure 5-13. Through the intensity of the colour, magnitude of reflected tensile stress, σ_x , appears to reduce significantly as it propagates through the tiles.

Figure 5-13. σ_x (normal stress) distribution in the ceramic tiles at times of 0 μ s, 10 μ s, 17 μ s, 25 μ s, 35 μ s and 44 μ s respectively where blue boxes and red boxes represents compressive stress wave and tensile wave respectively.

Stress wave profile and the fracture pattern at tile 3 of F+ multiple ceramic module is compared. The stress wave profile (left) and fracture pattern (right) are similar as seen in Figure 5-14; the fracture pattern formed an arc in the direction of the tensile wave, indicating the fracture is caused by the tensile wave. The low fracture toughness of F+ makes it highly susceptible to tensile failure, thus damage is observed in tile 5; where the peak tensile stress is only 49 MPa.

Figure 5-14. Comparison of ceramic damage pattern and stress wave profile of the Tile 3.

Figure 5-15 shows Y-stress (normal stress σ_y) distribution in the ceramic tiles. In both F+ and T+ ceramic modules, cracking along y-axis is observed in tile 2. The crack pattern in tile 2 of Grade F+ and Grade T+ ceramic tiles are shown in Figure 5-16(a) and Figure 5-16(b). The fracture pattern is compared against σ_y wave in Figure 5-16(c). The fracture pattern matches with σ_y wave pattern, indicating the crack propagation across tiles is due to σ_y .

Figure 5-15. σ_y state of neighbouring ceramic tiles at 10 μ s, 13 μ s and 23 μ s respectively.

Figure 5-16. Fracture pattern of tile 2 of (a) Grade F+ (b) Grade T+ with white line indicating the crack path and (c) stress wave profile of simulation.

Table 5-7. Peak tensile stress measured in various tiles after impact.

Tile No	2	3	4	5
Peak σ_x (MPa)	378	190	145	49
Peak σ_y (MPa)	272	169	80	59

The peak tensile stress was measured for each tile and listed in Table 5-7. σ_x is consistently larger than σ_y except for tile 5 from the stress measured. Based on that results,

one will expect wave-like damage pattern for tile 2-4 and horizontal V-shaped damage pattern for tile 5. However, this is not the case.

Therefore, the time for which each of the stresses peaked, and the locations of the stresses is examined. Looking at the two stress profiles in Figure 5-17(a) and Figure 5-17(b), it is observed that in element A, the σ_y peaks before σ_x , while in element B, the reverse is observed. The result means that the damage can be caused by either σ_x or σ_y , depending on the location of the crack. After taking sixteen readings from various locations in each tile, the results are mapped in Figure 5-18. It is observed that in tile 2, it is σ_y induced crack dominant while tile 3, 4 and 5 is σ_x induced crack dominant, with few locations caused by σ_y . The observation corresponds with the experimental result seen in Figure 5-19. It is observed that two distinct damage patterns are observed, crack propagation from origin in Tile 2 and wave-like fracture pattern from tile 3 onwards.

Figure 5-17. Plot of σ_x and σ_y against time in (a) element A and (b) element B.

Tile 1	Tile 2	Tile 3	Tile 4	Tile 5	Tile 6
	Y Y Y Y	X X X X	Y X X X	X Y X X	
	X Y Y X	Y X Y X	X X X X	Y X X X	
	X Y Y X	X X X X	X X X X	Y X Y X	
	Y Y Y Y	X X X X	Y X X X	Y Y X X	

Figure 5-18. Schematic map indicating the stress which peaked first at marked location.

Figure 5-19. Illustration of dominating mechanism of fracture across ceramic tiles

Combining the abovementioned two findings, it is concluded that tensile wave generated during the impact process leads to fracture of neighbouring ceramic tiles. The fracture pattern is determined by the stress which peaks first at the specific location of a tile, while the damage radius is influenced by the fracture toughness of the tiles. Based on the results, the key to reduce damage radius is to either (1) reduce the incoming stress, or (2) increase fracture toughness of ceramic. As the stress generated is controlled by the incoming projectile, it is highly unlikely to confine the damage to the impact tile at higher level threats. It is observed that the initial drop of stress from tile 2 to tile 3 is the largest, therefore, designing the fracture toughness of the ceramic tiles to survive the stress experienced in tile 3 is an efficient choice. In this example, the fracture toughness of SiC that is required to survive at tile 3 location is approximately $7 \text{ MPa}\cdot\text{m}^{1/2}$. Moreover, the stress reduction is primarily observed at the interface, thus, an alternative solution is to increase the number of boundaries for the same distance. This means smaller tiles will enhance the survivability of neighbouring tiles.

5.5 Conclusion

Higher ceramic hardness results in better ballistic performance due to dwell time increase. When the ceramic hardness increases from HV 20.6 GPa to HV 24.4 GPa, the dwell time increases from $23 \mu\text{s}$ to $31 \mu\text{s}$, improving the mass efficiency from 1.52 to 1.73. Meanwhile, no obvious influence of fracture toughness on ballistic performance is found.

However, ceramic fracture toughness has a strong influence on the damage in the neighbouring tiles. When the ceramic fracture toughness increases from $2.8 \text{ MPa.m}^{1/2}$ to $7 \text{ MPa.m}^{1/2}$, the damage radius reduces from 420 mm to 138 mm. In addition, the damage of neighbouring tiles is controlled by tensile wave that is generated during the impact process. When the fracture toughness is $2.89 \text{ MPa.m}^{1/2}$ (F+ grade tile) the tensile stress generates cracks in four neighbouring tiles (tile 5), hence reduces the multiple hit capability of ceramic module significantly. Grade T+, with fracture toughness of $7 \text{ MPa.m}^{1/2}$, the tensile stress is only able to generate cracks in one neighbouring tile (tile 2), improving the multiple hit capability of the ceramic armour module.

Therefore, it is recommended for ceramic armour designer to optimize the ceramic material parameters by determining the minimum fracture toughness required to withstand tensile wave while maximizing the hardness of ceramic.

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Chapter 6 *

Effect of Hardness/Toughness of Backing Plate

In this chapter, the influence of backing plate hardness and fracture toughness on ballistic performance of ceramic armour was studied through experimentations and simulations. Increasing hardness improves the ballistic performance of ceramic armour, while fracture toughness has no influence the ballistic performance. The mechanism which the backing plate influences the ballistic performance of ceramic armour was investigated through simulations. The primary role of the backing layer is to sustain dwell through support of ceramic. Dwell termination is strongly dependent upon deformation of the backing layer, which is closely associated with backing hardness. The ballistic performance of the ceramic armour modules is mainly controlled by dwell time as the erosion rate of projectile is similar across all the penetration phases. The influence by backing fracture toughness on ballistic performance is overshadowed by backing hardness as backing fracture occurs late into the penetration process limiting its influence on ballistic performance.

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6.1 Introduction

Early work by Rosenberg et al. demonstrated that backing thickness and strength influence the ballistic performance of ceramic. The study was based on thick backing, with 80mm steel backing and 7.62 mm rifle rounds, where higher strength backing resulted in better ballistic performance due to ceramic defeat mechanism being heavily influenced by backing [1]. Strassburger et al. conducted a series of experiments to compare ballistic performance of SiC ceramics with three different backing materials (harden steel, aluminium, and composite) against 7.62 mm projectile. They concluded that there was a correlation between duration of dwell phase and strength of backing layer [2].

It is also known that long rod projectile has different defeat mechanism compared to low level threat projectile [3–4] such as 7.62 mm calibre rifle round, thus it is of interest to understand if such correlation extend into long rod projectile. Studies on alumina/metal laminate were conducted by Ubeyli et al. and their works conclude that hardness of metallic backing has influence on the armour and AISI 4340 of HRC 40 and HRC 50 gave best performance [5–7]. These studies showed that hardness of backing did influence the ballistic performance of ceramic armour.

This chapter studies the influence of the backing plates hardness and fracture toughness on ballistic performance of ceramic armour against long rod projectile. Simulations and experiments were conducted to reveal the defeat mechanisms of long rod projectile by ceramic armour.

6.2 Ballistic Target

Figure 3-37 shows the single tile ceramic armour module used in the experiment. Table 6-1 lists the test matrix. The cover plate and ceramic were fixed as AISI 4340 steel heat treated to HRC 30 and Grade F+ SiC respectively while the backing plate material consisted of AISI 4340 steel heat treated to HRC 30, 40 and 50.

The armour modules fabricated were tested using two-stage light gas launcher in the MJHSDL. A detailed description of the fabrication process of the experimental setup and target fabrication are listed in Section 3.2.2 and Section 3.2.3 respectively. After testing, the witness block was sectioned along the penetration line to measure the residual penetration for calculation of the mass efficiency, E_m . The calculation of mass efficiency is elaborated in Section 3.2.4.

Table 6-1. Test matrix for single tile module for study of ceramic hardness and fracture toughness on ballistic performance.

Test Set	Cover Plate	SiC Grade	Backing Plate
01	AISI HRC 30	Grade F+	AISI HRC 30
02	AISI HRC 30	Grade F+	AISI HRC 40
03	AISI HRC 30	Grade F+	AISI HRC 50

6.3 Experimental Results

A series of experiments were conducted to study the influence of hardness and toughness of backing plate on ballistic performance of ceramic armour. Three tests were carried for each of the hardness HRC 30, 40 and 50. The experimental results are listed in Table 6-2 below.

The ceramics used in this study was done using the SiC batch purchased in 2012, which was of different batch from the ceramic and cover plate study. It was observed that the mass efficiency was lower for this batch of ceramics, however the results are consistent within the batch. A plot of the experimental results is shown in Figure 6-1. From the plot, the mass efficiency increases from 1.28 to 1.84 when backing hardness increases from HRC 30 to HRC 50.

Table 6-2. Experimental results of different backing hardness and mass efficiency.

S/N	Hardness (HRC)	Velocity (m/s)	DOP _{reference} (mm)	DOP _{residue} (mm)	E _m
B30-1	30	1244	64.2	27.0	1.28
B30-2	30	1244	64.2	27.0	1.28
B30-3	30	1286	68.8	30.0	1.30
B40-1	40	1263	66.3	27.0	1.32
B40-2	40	1256	65.5	19.0	1.56
B40-3	40	1256	65.5	19.5	1.54
B50-1	50	1229	62.6	11.5	1.81
B50-2	50	1246	62.7	10.0	1.95
B50-3	50	1235	64.4	12.8	1.76

Figure 6-1. A plot of mass efficiency against back plate hardness.

Figure 6-2 shows a plot of mass efficiency against backing fracture toughness. Decreased ballistic performance are observed when fracture toughness increases from the graph. This result is opposite of what one will expect. It is known that the fracture toughness and hardness are inversely related, i.e. increased hardness will result in reduced fracture toughness and vice versa. Therefore, it is hypothesized that the influence of

backing fracture toughness is overshadowed by the influence of backing hardness. It is impossible to obtain a material that can have its hardness modified without affecting its fracture toughness through experiment, this hypothesis is validated through simulation.

Figure 6-2. Plot of mass efficiency against back plate fracture toughness.

A comparison is made between the backing of ceramic armour after ballistic testing. It is observed that HRC 30 backing has significant bulging while HRC 50 backing has insignificant bulging as seen in Figure 6-3. The increased backing fracture toughness allows in more deformation before failure.

Figure 6-3. Top view and side view of backing with hardness of HRC 30 and HRC 50 after test.

Figure 6-5 shows the process of projectile penetrating the target. The first frame is determined to be the frame before the projectile impacts the cover plate. With high-speed video recorded at 150,000 fps, the time between frames was 6.67 μ s. Based on the high-speed image, no backing deformation is observed for the initial period of 40 μ s. During the time, the projectile tail moved a distance approximately half its length into the target. This phenomenon can be interpreted by the illustration in Figure 6-4. During dwell, the ceramic tile remains intact, it undergoes slight deformation under impact loading. This is due to high Young's modulus of SiC thus minimal backing deformation is seen in Figure 6-4(a). During penetration phase, the fractured ceramics in front of the projectile are pushed by the projectile. Due to insufficient time for the fragments to move out of the way, these fragments are pushed towards the backing, creating a bulging effect seen in Figure 6-4(b). This is supported by simulation when dwell is on-going at 41 μ s, slight bulge is observed at the backing as seen in Figure 6-6.

Figure 6-4. (a) Minimum deformation at backing during dwell phase and (b) backing deformation after fracture of ceramics.

At $47\text{ }\mu\text{s}$, the bulging of the backing is observed. The bulging grows rapidly after that. At $74\text{ }\mu\text{s}$, the bulge measured is 10 mm. The bulging is significant considering the backing thickness is only 10 mm. This corresponds to the phase of penetration, where the backing yields, and large deformation occurs.

The target perforated at $87\text{ }\mu\text{s}$, indicated by the first flash of light appearing at the rear of the target. Although the time which the backing fails was identified, the exact position of the projectile cannot be determined due to the bright flash, which masked the exact position of the projectile as seen by the frame at $113\text{ }\mu\text{s}$. The time which the projectile impact the witness block was $147\text{ }\mu\text{s}$. This was identified by the sudden bright flash propagating from the surface of the witness block.

Although these images have limitations, such as bright flashes and opaque target, they provide details such as backing deformation and target perforation time which is valuable to validate simulation results.

Figure 6-5. High speed image of projectile impacting target at 0 μ s, 27 μ s, 40 μ s, 47 μ s, 74 μ s, 87 μ s, 113 μ s and 147 μ s.

Figure 6-6. Image of simulation at 41 μ s.

6.4 Simulation

Simulation of the penetration process was carried out using hydrocode LS-DYNA. The model was built using LS-Prepost. The projectile was SPH while the rest of the model was modelled using FEM. The SPH size and the FEM mesh size were 0.4 mm and 0.8 mm respectively. The mesh size and particle size were not further reduced due to the constraint of computation time. The output timing was 1 μ s and the termination time is 180 μ s. Detailed explanation of the simulation model is listed in Section 3.3.1 while the material model is discussed in Section 3.3.2.

6.4.1 Simulation results

A comparison between simulation results and experimental results are plotted in Figure 6-7. The simulation results have higher mass efficiency than the experimental results as the simulation results are fitted against the ceramic tiles used for the experiments in Chapter 4 and Chapter 5 as more experiments are conducted using the new batch of ceramic thus providing better confidence in the simulation results. These differences are attributed to the batches of tiles used for experiment. The study of the backing was conducted using tiles purchased in 2012, while the cover and ceramic studies were conducted using tiles purchased in 2016. The batch purchased in 2012 had lower performance than the batch purchased in 2016. Despite the difference in mass efficiency, both experiment and simulation have identical trend. Both experiment and simulation

show improvement of ballistic performance with increased backing hardness. The mass efficiency increased by 0.56 and 0.51 for the experiment and simulation results respectively when backing hardness increases from HRC 30 to HRC 50.

Figure 6-7. A plot of mass efficiency of ceramic armour module against backing plate hardness for experiment and simulation results.

6.5 Mechanism

Simulations were carried out using hydrocode LS-DYNA for the penetration process of the ceramic armour. The results are shown in Figure 6-8. From Figure 6-8, the damage of the ceramic is shown at 4 instances, 15 μ s, 30 μ s, 45 μ s and 60 μ s. The damage scale is from 0 to 1, when $D = 0$, the ceramic is in intact state, i.e. within elastic region, when $0 \leq D \leq 1$, the ceramic has accumulated plastic deformation but did not exceed the maximum allowable plastic deformation and when $D = 1$ the ceramic has failed meaning the ceramic cannot withstand any tensile stress.

The damage of ceramic is governed by the equation below,

$$D = \sum \Delta \varepsilon_p / \varepsilon_p^f \quad \text{Equation 6-1}$$

where ε_p is the accumulated plastic strain and ε_p^f is the maximum plastic strain at failure.

Figure 6-8. A schematic of the damage process within the ceramic at, (a) 15 μ s, (b) 30 μ s, (c) 45 μ s and (d) 60 μ s [8].

Three phases of damage are observed in Figure 6-8. The first phase is at 15 μ s. During the initial impact by the long rod projectile, sub-surface damage was created directly beneath the area of impact. This sub-surface damage region is known as comminution zone shown in Figure 6-9. This zone is confirmed experimentally by Shih et al. [9] experimentally as shown in Figure 6-10. This comminution zone is an area with lots of fine cracks. Although the ceramic is cracked within the region, these cracks are confined within the ceramic by the neighbouring material. Due to the confinement, the damage does not propagate further. This prevents the ceramic from giving way, allowing dwell to occur.

Figure 6-9. Comminution zone in ceramic during simulation.

Figure 6-10. Experimental picture of comminution zone in a ceramic by Shih et al. [9].

The second phase is damage accumulation at the rear surface of the ceramic tile. This is seen in Figure 6-11. The damage within the comminution zone does not grow but the damage zone from the rear grows during 25 μ s to 45 μ s. The damage zone starts out as a narrow region as seen in 25 μ s. The damage region of the tiles broadens significantly, approximately doubling the damage diameter, between 25 μ s to 35 μ s forming a cone-like structure. At 45 μ s, it is observed that certain region within the damage zone was red, indicating $D = 1$. Although this region has failed, the confinement by the neighbouring material prevent dwell termination.

Figure 6-11. Ceramic damage profile at, (a) 25 μ s, (b) 35 μ s and (c) 45 μ s.

The third phase is dwell termination, i.e. penetration of ceramic. As the damage extends from the rear surface of ceramic, the damage zone connects with the comminuted zone, removing the confinement provided by the ceramic, allowing penetration to occur. This is shown in Figure 6-8(d), where the damage region, ($D = 1$) extends from the rear face to the impact face of the ceramic.

This is in agreement with the theory by LaSalvia [10]. In the paper, the author hypothesized that ceramics with thickness between 2 – 6.5 times of projectile radius will experience dwell termination due to rear surface damage extending toward the front face coupled with some degree of failure from rear support or interface as shown in Figure 2-8. In the experiment and simulation, the ceramic thickness to projectile diameter ratio is 4.8, in agreement with the range given by LaSalvia.

Based on the three phases of dwell/penetration explained above, it is understood that the role which a backing plate played within a ceramic armour is to support the ceramic tile. The loss of support, i.e. bending of backing results the termination of dwell in ceramic.

6.6 Discussion

6.6.1 Backing Plate hardness

The plastic strain at the interface between steel backing and ceramic along the penetration axis is obtained from simulation. The plastic strain is plotted against time as shown in Figure 6-12. The dwell termination time is indicated using dotted line and the intercept between the dotted line and plastic strain curve is the amount of plastic strain before termination of dwell. It is observed that the termination of dwell occurs when the plastic strain reaches 0.008. This is observed across all the hardnesses. It is observed for higher hardness backing, the plastic strain accumulation occurs later. As hardness correlates to yield strength of steel, as seen in the work by Deniz and Yildirim [11], where the parameter A of JC model, (yield strength), correlates with hardness of AISI 4340 steel with the equation below,

$$A = e^{0.0355 \cdot \text{HRC} + 5.5312} \text{MPa} \quad \text{Equation 6-2}$$

Although the equation is obtained empirically, it establishes the correlation between hardness and yield strength of steel. The higher yield strength results in delayed onset of yielding, extending dwell time. Moreover, the higher hardness has a slower increment rate of plastic strain as seen in Figure 6-12. These result in increased dwell time with increased backing hardness.

Figure 6-12. Plastic strain of different hardness backing was plotted against time, where the dwell termination time for each hardness is represented with dotted line. The red line is reference line indicating accumulated plastic strain of 0.008 [8].

A comparison is made between the HRC 30 and HRC 50 backing ceramic armour module at times 0 μs , 30 μs , 60 μs and 90 μs in Figure 6-13. Between the duration of 0-30 μs the damages are identical for both hardnesses backing. At 60 μs , the projectile is observed to penetrate at least half of the ceramic thickness for HRC 30 backing while for HRC 50, the projectile only starts penetrating the ceramic. HRC 30 backing is observed to experience more deformation than HRC 50 backing. At 90 μs , the projectile has fully penetrated the ceramic layer for HRC 30 backing while the projectile is three quarter through the ceramic thickness for HRC 50 backing. The relative position of projectile tip from time 60 μs and 90 μs is observed to be almost identical, indicating that the erosion rate in the ceramic is independent of the backing hardness.

Figure 6-13. Comparison of relative projectile positions and damage of ceramic between modules with backing hardness of HRC 30 and HRC 50 at, (a) 0 μs , (b) 30 μs , (c) 60 μs and (d) 90 μs after projectile impact [8].

A plot between the position of the projectile tip position against time is drawn, comparing across different hardness backing in Figure 6-14. The reference point, displacement = 0, is taken as the top surface of the cover plate and time = 0 is taken at the time which the projectile impacts the cover plate. From the plot, the gradient at all the penetration phases, i.e. penetration of cover plate (0 μs – 10 μs), dwell (10 μs – 50 μs) and penetration of ceramic (50 μs – 70 μs) are the same. This indicates the erosion rate across all these phases are independent of the hardness of backing. The primary difference is the time of transition from dwell to penetration. These observations lead to the conclusion that increased ballistic performance is due to improved dwell time due to better support of ceramic from higher hardness backing.

Figure 6-14. A plot of projectile tip displacement against time for different hardness backing at 1 μ s interval, where there are three distinct phases (1) cover plate penetration, (2) dwell and (3) ceramic penetration.

6.6.2 Backing Plate Fracture Toughness

It is a material limitation where increased hardness will couple with decreased fracture toughness, thus it is impossible to conduct experiment with only one parameter changed. A series of simulations were carried out to study the influence of backing plate fracture toughness on ballistic performance instead. The fracture toughness chosen was 120, 90, 60, 30, 10 and 5 $\text{MPa}\cdot\text{m}^{1/2}$ respectively for hardness of HRC 30 and HRC 50. The results are plotted in Figure 6-15. The mass efficiency of ceramic armour decreased from 1.56 to 1.48 for HRC 30 and 2.35 to 2.17 for HRC 50 when backing plate fracture toughness reduced from 120 $\text{MPa}\cdot\text{m}^{1/2}$ to 51 $\text{MPa}\cdot\text{m}^{1/2}$.

The influence of fracture toughness is observed to be greater for higher hardness, where for the same amount of reduction of fracture toughness, 120 $\text{MPa}\cdot\text{m}^{1/2}$ to 51 $\text{MPa}\cdot\text{m}^{1/2}$, the mass efficiency drops by 0.08 and 0.18 for HRC 30 and HRC 50 respectively. This is due to higher hardness backing corresponding to higher ultimate tensile stress, resulting in a larger area under the curve as seen in Figure 6-16. This means the amount of deformation energy is larger for higher hardness, thus increasing the percentage of projectile kinetic energy loss to backing.

Figure 6-15. A plot of mass efficiency against fracture toughness of backing plate (simulation results).

Figure 6-16. A plot of stress against strain for backing steel of hardness HRC 30 and HRC 50.

A history plot of the kinetic energy in the projectile is shown in Figure 6-17. In the plot, the two cases being compared are (a) hardness HRC 50 backing with fracture toughness of 51 MPa.m^{1/2} and (b) hardness HRC 50 backing with fracture toughness 120 MPa.m^{1/2}. From the plot it is observed that the energy reduction rate was identical for

both cases for the initial 100 μs . This demonstrates that fracture toughness of backing has minimal influence on the dwell phase and ceramic penetration phase. During these phases, the plastic deformation is well below the failure threshold for the respective fracture toughness, therefore it has little to no influence during the two phases mentioned above.

However, after 100 μs , it is observed that higher backing fracture toughness has a larger drop in projectile kinetic energy. The region shaded in blue in Figure 6-17 represents the energy reduction difference for projectile. This energy difference contributes to the difference in ballistic performance.

100 μs in the simulation corresponds to the point where the projectile begins penetrating the backing plate as seen in Figure 6-18. This indicates that the difference in energy loss observed is during the penetration of backing by projectile. This energy loss is attributed to deformation energy of the backing, as seen in Figure 6-19, where a plot of backing stress against backing plastic strain is plotted. From the graph, it is observed the area under the stress strain curve, i.e. energy absorb per unit volume, is around 2.4 times smaller for the lower fracture toughness result. This indicates that the difference between the kinetic energy of projectile is due to the deformation energy in the backing.

Figure 6-17. Plot of projectile kinetic energy against time for different backing fracture toughness.

Figure 6-18. Location of projectile in target at 100 μ s.

Figure 6-19. Plot of backing stress against backing strain, where area under stress-strain curve for $K_{Ic} = 51 \text{ MPa.m}^{1/2}$ is shaded in red and $K_{Ic} = 120 \text{ MPa.m}^{1/2}$ is the total area shaded in red and blue.

Although the influence of backing fracture toughness is seen in simulation, it is however not observable from experimental results. It is hypothesized that the influence of backing fracture toughness is overshadowed by the influence of backing hardness.

Therefore, to prove the above hypothesis, two conditions: (1) different hardness with reduced fracture toughness accounted and (2) different hardness without account for influence of fracture toughness were simulated. The results are shown in Figure 6-20. From the plot, when the reduction of fracture toughness is not accounted for, the mass efficiency

increases from 1.66 to 2.35 when hardness increases from HRC 30 to HRC 50 while for the case where the fracture toughness of backing plate is accounted for, the mass efficiency increases from 1.66 to 2.17. From the results, two conclusions are drawn; (1) by increasing backing hardness from HRC 30 to HRC 50, the mass efficiency increases by 0.69 and (2) the reduction of fracture toughness from $120 \text{ MPa.m}^{1/2}$ to $51 \text{ MPa.m}^{1/2}$ decreases the mass efficiency by 0.18. As the influence of hardness (0.69) is greater than fracture toughness (0.18), it overshadows the influence of backing plate fracture toughness.

Figure 6-20. Plot of mass efficiency against backing plate hardness where red data points accounted for fracture toughness and blue data point exclude influence of fracture toughness reduction.

Therefore, fracture toughness of backing does reduce ballistic performance of a ceramic armour but the penalties which come with decreased fracture toughness is outweighed by the increased backing hardness. The primary reason for hardness to have greater influence on ballistic performance of ceramic armour than fracture toughness is due to hardness is improving the dwell phase, i.e. the most efficient phase of projectile penetration, while fracture toughness affects the erosion through backing deformation energy, which is a less efficient mechanism. Therefore, it is more favourable to increase hardness of backing plate to achieve the maximum mass efficiency.

6.7 Conclusion

Increased backing plate hardness improves the ballistic performance of the ceramic armour. The improvement is caused by increased dwell time. Increased dwell time is due to better support provided by the backing plate. For fracture toughness, the ballistic influence is not observed through experiment.

The backing plate fracture toughness study was carried out using simulation. Through simulations, decreased fracture toughness leads to reduce ballistic performance of ceramic armour. The decrease is due to lesser deformation energy at the backing plate for lower fracture toughness. However, the reduced ballistic performance for backing plate fracture toughness reduction is less than the improvement which comes with the increased hardness, therefore, it is more favourable to increase backing hardness than increase backing fracture toughness.

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Chapter 7

Design Optimization

In this chapter, the optimization process for ceramic armour will be discussed. The optimization process was carried out in simulation. This chapter bring all the conclusions drawn in previous chapters together, forming a systematic process of armour design. The design process is separated into two distinct phases; (1) cover plate and (2) ceramic/backing ratio optimization. The cover plate optimization focused on achieving maximum dwell time to AD ratio, achieving the most efficient cover plate configuration. The ceramic/backing ratio optimization focuses on the balance between dwell time optimization and DOP. With the major components of the ceramic armour module optimized, the best ceramic armour configuration for the tested projectile is determined.

7.1 Introduction

In this chapter, the optimization process of a ceramic armour module was carried out using simulation. With the knowledge gained in the process of studying the effect of hardness and toughness of ceramic armour, a scheme to systemically optimize ceramic armour is developed. The trend observed during optimization process provided insights to the changes in mechanism during tuning of the ceramic armour configurations. These insights will allow both armour optimization for the tested projectile and act as a guideline for armour design against other threats of long rod projectiles.

7.2 Cover Plate Optimization

Cover plate is an essential piece for establishment of dwell in ceramic armour. The dwell-penetration transition velocity can increase by at least 200 m/s with a cover plate, in some cases, the increase can go up to 700 m/s [1–2]. Therefore, having a good cover plate design is essential. The optimization process of cover plate is carried out in two phases: (1) material properties (hardness and fracture toughness) and (2) thickness optimization.

In Chapter 4, it was concluded that the performance of cover plate is influenced by fracture toughness, where reduced fracture toughness will jeopardise the ceramic armour performance. On top of that, the ballistic performance of ceramic armour is not influenced by the cover plate hardness. Therefore, a series of simulations were carried out to find the minimum cover plate fracture toughness needed for no sudden drop of impact pressure. As this sudden drop of pressure to prematurely terminate the dwell phase.

The history of the impact pressure of the ceramic in front of the tip of the projectile was obtained from simulation. Figure 7-1 shows impact pressure history for cover plate fracture toughness of 50, 70 and 90 MPa.m^{1/2}. The sudden drop of impact pressure occurs for both fracture toughness 50 MPa.m^{1/2} and 70 MPa.m^{1/2} and not 90 MPa.m^{1/2}. Therefore, it is recommended to have fracture toughness of the cover plate above 90 MPa.m^{1/2} to prevent early dwell termination.

Figure 7-1. Impact pressure on ceramic surface against time for cover plates with fracture toughness of 50, 70 and 90 MPa.m^{1/2}.

It is known that the hardness and fracture toughness have an inverse relationship, i.e. increased hardness will result in decreased fracture toughness and vice versa. A plot of fracture toughness versus hardness for AISI 4340 steel is shown in Figure 7-2. The obtained test data in this study is consistent with that from literature [3]. It is noted that fracture toughness for the points shown in Figure 7-2 were obtained from the single edge notch (SEN) experiment. The results show that the decrease in fracture toughness becomes significant when hardness exceeded HRC 45. A point marked X on the curve in Figure 7-2, indicates the point where $K_{Ic} = 90 \text{ MPa.m}^{1/2}$ which corresponds to HRC 47. As $K_{Ic} = 90 \text{ MPa.m}^{1/2}$ is the lowest fracture toughness that does not have sudden pressure drop (Figure 7-1); consequently, it is recommended that the cover plate hardness should not exceed HRC 45 for steel 4340 so that the fracture toughness is sufficiently high (greater than 90 MPa.m^{1/2}) to prevent early dwell termination in ceramic armour.

Figure 7-2. A plot of fracture toughness against hardness of AISI 4340.

After determining the cover plate hardness/fracture toughness, the thickness of the cover plate is optimized. As mentioned in previous chapters, the ballistic performance of the ceramic armour module is dependent on the dwell time. To determine the optimized performance, the dwell time for different cover plate different thicknesses were studied. The results are listed in Table 7-1. A parameter, ratio of the dwell time to AD, in the table is used to provide a quantitative factor to determine optimized thickness. The units of dwell time and AD are μs and g/mm^2 respectively.

The results from Table 7-1 shows that dwell no longer occurs when the cover plate thickness is lesser than 1.6 mm. This phenomenon can be explained by Figure 7-3, where the impact pressure exceeds the Hugoniot elastic limit $HEL = 11.7 \text{ GPa}$ at $7 \mu s$. The impact pressure of 14 GPa exceeds the dynamic strength of the ceramic, thus generating cracks and prevents dwell phenomenon from occurring.

Table 7-1. Results of dwell time for different thickness cover plate.

Cover Plate Thickness (mm)	Areal Density (kg/m ²)	Dwell Start Time (μs)	Dwell End Time (μs)	Total Dwell Time (μs)	Dwell Time /AD ratio
8.3	65.2	17	41	24	0.368
5	39.3	10	41	31	0.789
4.1	32.2	10	44	34	1.055
3.2	25.1	9	45	36	1.434
2.5	19.6	8	44	36	1.836
1.6	12.6	-	-	0	0

Figure 7-3. Impact pressure on ceramic surface for 1.6mm cover plate.

The dwell time is plotted against cover plate thickness in Figure 7-4. From the graph, it is observed that thicker cover plate does not necessary equate to longer dwell time. The dwell time remains rather consistent varying between 31 μs to 36 μs for cover plate thickness ranging between 2.5 mm to 5 mm. However, for cover plate thickness of 8.3 mm, the dwell time decreased rapidly to 24 μs. To understand the cause of this rapid decrease, the simulation results are analysed. The damage profiles of the ceramic at 1 μs before dwell termination for cover plate thicknesses of 2.5 mm and 8.3 mm are shown in Figure 7-5.

According to the damage profile, the damage for 2.5 mm cover plate is about to connect from the ceramic rear face to the comminution zone near the surface of the ceramic. This is identical to the mechanism shown in Chapter 6. However, for 8.3 mm cover plate, the damage zone is far from connecting from the rear to the ceramic surface. This is an indication of premature dwell termination. Through analysis of the deformation profile of the cover plate in Figure 7-6, it is observed that the thickness of 8.3 mm cover plate has worked against its performance. The thickness limits deformation of the cover plate, preventing the characteristic flow of eroded material in the lateral direction which is observed in Figure 7-6(a) for thinner cover plate. The eroded material is confined within the cavity of the of the cover plate, which forces the material downwards towards the ceramic, leading to premature dwell termination for thicker cover plate. The result is consistent with work conducted by Hauver et al. [4] and Espinosa et al. [5–6], where in their studies, a thin layer of soft material was inserted between the cover plate and the ceramic to achieve interface defeat in ceramic armour. This allows lateral flow of material, thus preventing premature dwell termination in the experiment.

Figure 7-4. A plot of dwell time against cover plate thickness.

Figure 7-5. Damage profiles of ceramic before dwell termination for (a) 2.5 mm thick cover plate and (b) 8.3 mm thick cover plate.

Figure 7-6. Magnified image of cover plate profile for (a) 2.5 mm thick cover plate and (b) 8.3 mm cover plate where the flow direction of the eroded material is indicated with red arrows.

According to Table 7-1, 2.5 mm thick cover plate is the best choice for cover plate design with the highest dwell time to AD ratio of 1.836. Thus, for the optimization of the ceramic and backing process, the cover is fixed at 2.5 mm thick with hardness and fracture toughness of 45 HRC and $100 \text{ MPa}\cdot\text{m}^{1/2}$.

7.3 Ceramic and Backing Optimization

Ceramic and backing are shown to have the best performance when the measured hardness is highest in Chapter 5 and 6. The hardness selected for the backing is HRC 50, based on the findings in Chapter 6; for the SiC, the properties selected for single tile module is Grade F+, which had hardness of 24.4 GPa as seen in the work done in Chapter 5. As ceramic performance is highly influence by the backing conditions, i.e. thickness and strength [7–10], it is impractical to optimize ceramic and backing separately. Thus, a series of simulations were conducted to optimize the ratio between ceramic thickness to backing thickness while keeping the AD constant.

The simulation matrix is shown in Table 7-2. The cover plates used in all cases were 2.5 mm thick AISI 4340 steel determined in Section 7.2. The analysis of the ceramic and backing base on two criteria, dwell time and DOP.

Table 7-2. Simulation matrix for ceramic/backing thickness ratio optimization.

Set No	Ceramic Thickness (mm)	Backing Thickness (mm)	Ceramic / Backing Ratio	Ceramic %wt	Total Thickness (mm)
1	10	14	0.71	19.8	26.5
2	15	12	1.25	29.7	29.5
2	20	10	2	39.5	32.5
3	25	8	3.13	49.3	35.5
4	30	6	5	59.0	38.5
5	35	4	8.75	68.7	41.5
6	40	2	20	78.3	44.5

7.3.1 Dwell Time

In the previous chapters, it is concluded that the ballistic performance is primarily controlled by the dwell time. Therefore, dwell time for all the different configurations were obtained through simulation and listed in Table 7-3.

Table 7-3. Dwell time for different ceramic armour configurations.

Set No	Ceramic Thickness (mm)	Backing Thickness (mm)	Ceramic / Backing Ratio	Dwell Time (μ s)
1	10	14	0.71	10
2	15	12	1.25	26
3	20	10	2	48
4	25	8	3.13	48
5	30	6	5	42
6	35	4	8.75	41
7	40	2	20	39

The results in Table 7-3 shows that the dwell time is heavily influenced by the ceramic to backing thickness ratio. It is observed that the dwell time is longest when the ceramic-backing ratio is ~ 3 . The results are plotted in Figure 7-7. From the plot, two distinct slopes are observed. The first slope is when ceramic to backing thickness ratio is between 0.5 to 3 and the second slope is from 5 to 20. The first slope has a steep increase in dwell time while the second slope has a very gradual decrease of dwell time.

Figure 7-7. A plot of dwell time against ceramic/backing thickness ratio.

To understand the trend observed, the damage profile of ceramic is studied. Figure 7-8 shows the profile of 10 mm, 25 mm and 35 mm thick ceramic just before dwell termination. For thinner ceramics, dwell termination occurs when the damage region connects from the rear face to the front face of ceramic seen in 10 mm SiC. When ceramic thickness increases, two phenomena are observed: (1) the damage propagation is slower; 15 mm tile experiences some failure ($D = 1$) at 25 μs while 25 mm tile has barely any damage accumulation at the same time (Figure 7-9) and (2) damage propagation took a longer path to connect to the front face of ceramic, i.e. the path distance is the thickness of the ceramic (Figure 7-8). Slower damage propagation is due to the higher stiffness of the ceramic armour module which results in lesser deformation of armour structure. The longer path is due to the thickness of ceramic, longer time will be needed to travel the distance. Dwell termination occurs due to damage connecting from the rear to the front surface, increased ceramic thickness is translated to significant increase in dwell time as the process of damage connection is delayed.

However, this is not the case for ceramic thicker than 30 mm. From Figure 7-8, although damage accumulation occurs at the back face of ceramic, the damage did not propagate through the tiles. The high stiffness of the ceramic provides sufficient support,

preventing the damage from loss of backing support. Instead, failure occurs at the surface of the ceramic. The outcome is similar to the prediction by LaSalvia [8], where it was predicted that a transition of dwell termination mechanism according to the normalized thickness of ceramic, however in his work he was working on the transition of ideal “thick tiles”, i.e. semi-infinite thick ceramic. With increased thickness, the damage at the rear is observed to decrease as seen in Figure 7-10. The damage for 40 mm tiles is significantly lesser than the 30 mm tiles. The slight reduction of dwell time for ceramic is due to better support of thick ceramic, allowing the peak stress to be reached earlier as seen in Figure 7-11. The peak stress of 40 mm tile occurs at $45\ \mu\text{s}$ while 35 mm tile occurs at $47\ \mu\text{s}$, which corresponds to the $2\ \mu\text{s}$ difference in dwell time measured, validating the hypothesis of better support which results in peak stress achieve at an earlier time.

Therefore, according to the observed trend, it is predicted that dwell time reduction due to ceramic thickness will stop when the ceramic reaches the ideal “thick ceramic”, i.e. when there is no deformation at the ceramic rear surface.

Figure 7-8. Damage profiles of 10 mm, 25 mm and 35 mm tiles one frame before dwell termination.

Figure 7-9. Damage profiles of 15 mm and 25 mm ceramic at 25 μs.

Figure 7-10. Damage profiles of 30 mm and 40 mm thick ceramic at instance of dwell to penetration transition.

Figure 7-11. A plot of impact pressure against time for 35 mm and 40 mm thick SiC tiles.

7.3.2 Depth of Penetration

The residual DOP was measured for all the ceramic armour modules. The results are listed in Table 7-4. From the simulation results, residual DOP is observed to decrease with increasing ceramic thickness, with 40 mm tile configuration totally defeat the projectile without perforation. Although both 35 mm and 40 mm tiles have DOP = 0 mm the results are very different. For 35 mm tile configuration, the projectile perforates the target and impacts the witness block, while 40 mm tile configuration, the projectile stops after penetrating through 30 mm of tile as seen in Figure 7-12 . Therefore, it is concluded that the configuration with the 40 mm tile has the best performance.

The results are plotted in Figure 7-13. The ballistic performance of ceramic armour is seen to increase significantly when the ceramic thickness is doubled, from 10 mm to 20 mm, the residual DOP reduces from 28 mm to 5.6 mm, a reduction of 80 % in DOP. Correlating the results from previous section, the large improvement in performance is due to the increased dwell time. The dwell time increased from 10 μ s to 48 μ s, an increase of 380 % dwell time, which translates to approximately 45 mm more of the projectile erosion during the dwell phase. From these results, it is concluded that for the ceramic armour to

be efficient, the ceramic thickness must exceed certain thickness for effective performance, which is 20 mm in this case.

Table 7-4. Simulation results of different ceramic armour configurations.

Set No	Ceramic Thickness (mm)	Backing Thickness (mm)	DOP(mm)
1	10	14	28
2	15	12	18
3	20	10	5.6
4	25	8	2.8
5	30	6	5.8
6	35	4	0.0 ¹
7	40	2	0.0 ²

Figure 7-12. Damage condition of ceramic armour after projectile defeated.

To understand the rest of the results for ceramic armour performance, the length of projectile during the following phases: (1) start of dwell, (2) end of dwell and (3) perforation of ceramic was measured to obtain the length of projectile eroded during each phase. The results are shown in Table 7-5. The length of projectile eroded per mm of SiC is observed to be similar for all configurations ranging between 1.5 mm/mm to 1.8 mm/mm, averaging at 1.64 mm/mm.

¹ Target was perforated

² Target was not perforated

Figure 7-13. A plot of ceramic thickness against residual DOP.

Table 7-5. Projectile length of different configurations ceramic armour module at various stages of penetration.

SiC Thickness (mm)	Projectile Length (mm)			Projectile length eroded per mm SiC (mm/mm)
	Dwell End	After SiC perforation	Length eroded by SiC	
10	98	82	16	1.6
15	79	52	27	1.8
20	53	19	34	1.7
25	52	13	39	1.6
30	60	13	47	1.6
35	60	8	52	1.5
40	61	9	52	1.7 ³

With the above information on dwell time and erosion rate of ceramic, the increase in 1 μ s of dwell time translates to 1.25 mm of projectile erosion while increasing 1 mm of

³ The projectile length eroded per mm SiC was obtained by dividing projectile length eroded by SiC by 30 mm instead of the ceramic thickness of 40 mm

SiC will increase projectile eroded by 1.64 mm. According to Figure 7-7, the difference in dwell time between 25 mm and 40 mm thick ceramic was 9 μ s which approximates to a difference of 11.3 mm eroded projectile. However, the addition erosion contributes to the added thickness of ceramic was 24.6 mm, which translates to an increase of 13.3 mm of eroded projectile when ceramic thickness increases from 25 mm to 40 mm. Therefore, despite shorter dwell time for thicker ceramics, thicker ceramics have better performance.

Base on ballistic performance, 40 mm backing plate couples with 1.8 mm backing has the best configuration under the condition of 162 kg/m². However, in design of ceramic armour, AD is a major but not the only concern. Other factors such as cost, and engineering limitation have a huge role in the determination of the final configuration of ceramic armour. Challenges such as higher cost of thicker ceramic and maintaining the ceramic properties while increasing its thickness. These challenges limit the feasibility of the suggestion of using thick ceramic given in the studies. Therefore, the option of 25 mm thick SiC with 8 mm backing may be a better solution for the actual armour design. With slight increase of AD, the cost can be lowered, and the engineering challenge can be overcome.

7.4 Conclusion

Based on the work carried out in Chapters 4, 5 and 6, optimization of ceramic armour design against long rod projectile was conducted. The optimization process has two phases: (1) cover plate and (2) ceramic/backing optimization.

The cover plate optimization establishes longest dwell with the lowest possible AD, while the ceramic/backing optimization provides an optimized solution with maximized dwell time and lowest DOP which was 2.5 mm thick AISI 4340 steel with hardness of HRC 45.

The ceramic/backing ratio optimization shows that increasing ceramic thickness is the key for best ceramic armour performance. However, the solution may not be feasible

due to engineering challenges and cost of fabricating ceramic of such thickness. Therefore, 25 mm tile configuration which has maximized dwell time and lowest DOP among ceramics with thickness between 10 mm to 30 mm is recommended as the alternative solution.

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Chapter 8

Conclusions and Recommendations

This chapter summarised the work that had been carried out for this entire study and the implications of the findings. It pieces together all the work, painting a single picture of the role which hardness and fracture toughness play in ballistic performance of ceramic armour. The future work regarding the extension of the correlation established in current studies onto oblique impact are also discussed in this chapter.

8.1 Conclusions and Implications

In summary, the influence of hardness and fracture toughness of the three main components of a ceramic armour module: (1) cover plate, (2) ceramic and (3) backing plate, on ballistic performance of ceramic armour were studied. The relationship of each property with ballistic performance was established through the understanding of the mechanisms of each component in the defeat of a long rod projectile. Through a combination of experimental work and computer simulations, it was found that a key influence of hardness and toughness of the components in an armour module is the dwell time of the projectile on the ceramic surface.

The cover plate attenuates the impact caused by the projectile, allowing dwell to be established on the ceramic surface. As shock attenuating property is not influenced by hardness, therefore, ballistic performance of ceramic hardness is independent of cover plate hardness. However, reduction of fracture toughness below $90 \text{ MPa.m}^{1/2}$ resulted in premature fracturing of cover plate, leading to the loss of confinement pressure, hence reduced ballistic performance.

For the ceramic, there are two defeat mechanisms: (1) erosion and (2) dwell. Hardness of the ceramic does not have any influence on the erosion rate of a projectile. However, the hardness of ceramic increases the dwell time, thus, improving ballistic performance of ceramic armour. Fracture toughness of ceramic does not influence the ballistic performance of ceramic armour as the fracture energy is insignificant compared to the projectile energy. However, fracture toughness of ceramic influences the damage radius significantly. The fracture of neighbouring tile is caused by tensile stress wave generated during the impact. The integrity of neighbouring tile correlates with increasing fracture toughness of the ceramic.

The backing plate provides support to the ceramic. Dwell time on ceramic surface is sensitive to the support the ceramic receives from the backing. Increased backing hardness leads to improve support, hence improved dwell time. This translates into better

ballistic performance. The influence of backing plate fracture toughness was not observed in experimental results. However, through computer simulation, it was observed that fracture toughness of the backing plate does influence the ballistic performance of ceramic armour through energy absorption as it deforms. The contribution by increased fracture toughness is significantly lesser than the contribution by the material hardness thus this effect was not observed in the experiment.

Combining the knowledge obtained through the studies conducted above, ceramic armour design optimization was carried out. The optimization process has two phases: (1) cover plate and (2) ceramic/backing optimization. The first phase obtains the maximum dwell time to AD ratio, finding the most efficient cover plate thickness. The second phase is to achieve the best performance ceramic to backing thickness ratio through two criteria; (1) dwell time and (2) DOP. The dwell time is heavily influence by ceramic thickness. The longest dwell time of 48 μ s was observed for 20 mm and 25 mm ceramic tiles. However, the longest dwell time does not translate to best ceramic armour performance. Instead, the ceramic armour with the thickest ceramic has the best performance. Although erosion phase is less efficient than dwell phase, the increase projectile length eroded by increase ceramic thickness compensates for the loss of dwell time. In fact, thicker ceramic configuration erodes more projectile. However, after the considerations of the feasibility and the cost of fabrication, thick ceramic may not be the ideal solution for practical armour applications. Instead, a compromised solution of using 25 mm thick ceramic configuration which has longest dwell time and lowest DOP among the 10 mm to 30 mm thick ceramic configurations is recommended.

8.1.1 Scientific Significance

Through the studies conducted, the hardness and toughness of various components of ceramic armour were systematically analysed and their relationship against ballistic performance of ceramic armour were established. As hardness and fracture toughness are often a trade off in materials, the knowledge of the roles which these properties play in ceramic armour is highly beneficial for ceramic armour designer.

These studies in Chapter 4, 5 and 6 address the gap of the role of hardness and fracture toughness under practical armour solutions, i.e. limited backing thickness and AD. On top of that, these studies focus on ceramic armour against long rod projectile instead of small calibre projectile used in other studies. As long rod projectile has very different defeat mechanism as compared to small calibre projectile, these studies provide insights to ceramic armour designers for designing ceramic armour against higher level threats.

Moreover, the correlation between ceramic hardness and strength parameters of JH-1 model, S_1 and S_2 were established, allowing studies of the hardness of ceramic to be conducted. This knowledge allows armour designers to incorporate hardness into their simulations for armour design, as for the studies conducted, it demonstrates that the ballistic performance of ceramic armour is heavily influenced by its hardness.

In Chapter 7, the design optimization process provides ceramic armour designer a fundamental guideline on armour design. The design process was broken down into two phases, allowing one to focus on one component at a time. The first phase focuses on cover plate. While many studies focused on the shift of dwell to penetration transition velocity by cover plate, this study focuses on the relationship between dwell time and cover plate thickness allowing the design optimization against specific threat. The second phase focuses on ceramic/backing optimization, where a shift of mechanism of dwell termination with ceramic thickness is observed. It provides insights into ceramic thickness selection and considerations during its optimization process.

8.2 Future Recommendations

8.2.1 Array Study

In this study, only two array experiments were carried out. Through the two experiments, the trend between ceramic fracture toughness and damage radius was established. However, due to the limited number of experiments, the conclusion is rather limited, more work can be done to expand on the conclusion gathered to answer questions

such as minimal fracture toughness to contain crack within impact tile, correlation between tile size, fracture toughness and damage radius and effect of energy damping layer between tiles. Many more studies can be carried out using the modified ceramic armour array module experiment, providing ceramic armour designer with better solutions and guidelines.

8.2.2 Oblique Impact

In this study, the focus was on normal impact, i.e. impact face is perpendicular to the projectile flight path. However, in actual armour there is a variant known as sloped armour. This type of armour capitalized on the geometry effect where the armour effectiveness is increased without weight increase. By having the armour at an angle, the path travels by the projectile is lengthened, improving the ballistic performance. These armours are commonly use at the front face of the armour where the probability of being hit is the highest [1]. Therefore, armour designer will place more focus on this part of the vehicle.

Due to the asymmetrical loading experience by the armour during an oblique impact, additional mechanisms such as fragmentation of projectile and ricochet of projectile may occur in a ceramic armour [2]. Therefore, more studies are required to understand if the relationship established could be transferred to oblique armour design.

8.2.3 Alternative Materials as Cover/Backing Plates

8.2.3.1 Titanium/Aluminium Cover Plate

From the current study, it was concluded that cover plate hardness does not influence ceramic armour module performance. Therefore, there is potential for using other materials such as titanium and aluminium which have lower density than steel, which was previously not considered due to their low hardness. If proven an effective cover plate

material, titanium and aluminium can mean massive weight saving for ceramic armour module.

8.2.3.2 Titanium Backing Plate

From the current study, it was concluded that higher backing plate hardness improves ballistic performance of ceramic armour module by improving support for ceramic. Another known method of support improvement is by increasing backing plate stiffness, i.e. backing plate thickness. Although titanium has lower hardness, it has a lower density than steel thus able to compensate reduced hardness with increased stiffness. Therefore, there is a possibility to expand the current conclusion on backing hardness to a combined factor of hardness and stiffness to have a more comprehensive coverage of backing materials.

8.2.3.3 Polyurea Enhanced Cover Plate

Polyurea due to its good strength and large elongation, it is commonly used for blast protection purpose [3–6]. However, despite its good properties, there is very limited work on using of polyurea in ceramic armour [7]. In recent testing, polyurea was integrated into the cover plate system of ceramic armour and the initial results is very promising. Of the two shots conducted, the mass efficiency was 2.58 and 2.71 respectively, while the typical mass efficiency of the reference ceramic armour module was around 1.5 to 1.7. The large increase in ceramic ballistic performance is very promising and worth the effort for further studies to understand how to effectively integrate polyurea into ceramic system and the mechanism which allow such large increase in ballistic performance. With deeper understanding of the mechanism, this could open up new possibilities to integrate other materials into ceramic armour system and design an improved ceramic armour system.

8.3 Publications List

- Goh, W. L., Zheng, Y., Yuan, J., & Ng, K. W. (2017). Effects of hardness of steel on ceramic armour module against long rod impact. *International Journal of Impact Engineering*, 109, 419–426.
- Yuan, J., Tan, G. E. B. and Goh, W. L. (2017) Simulation of Dwell-to-Penetration Transition for SiC Ceramics Subjected to Impact of Tungsten Long Rods, in *Advances in Ceramic Armor, Bioceramics, and Porous Materials: Ceramic Engineering and Science Proceedings Volume 37, Issue 4*.
- J Yuan, W.L. Goh, Y. Zheng, B. Luo & Z. Zeng (2017). Aluminium Block against Oblique Penetration of Tungsten Alloy Long Rod. *Proceeding of 30th International Symposium on Ballistics*, 2441-2448.
- Jianming Yuan & Wei Liang Goh (2016) Relation between Material Property and Dwell-to Penetration Transition Velocity for SiC Ceramics. *Proceeding of 29th International Symposium on Ballistics*, 2144-2154
- G.E.B. Tan, J. Yuan & W.L. Goh (2016) Steel-Confined SiC Armour against Oblique Penetration. *Proceeding of 29th International Symposium on Ballistics*, 2451-2457

8.4 Conference Presentations

- Oral presentation with the title “Influence of Hardness and Toughness of Ceramic on Performance of Ceramic Armour” at the “42th International Conference & Exposition on Advanced Ceramics and Composites” organized by American Ceramic Society (ACerS) in Florida, Daytona Beach, United State of America, Jan 20-26, 2018.
- Poster presentation with the title “Simulation of Dwell-to-Penetration Transition for Sic Ceramics Subjected to Impact of Tungsten Long Rods.” at the “40th International Conference & Exposition on Advanced Ceramics and Composites” organized by American Ceramic Society (ACerS) in Florida, Daytona Beach, United State of America, Jan 25-29, 2016.

- Poster presentation with the title “Relation between Material Property and Dwell-to-Penetration Transition Velocity for SiC Ceramics” at conference “29th International Symposium on Ballistics” organized by International Ballistics Society (IBS) in Scotland, Edinburgh, United Kingdom, May 9-13, 2016.
- Poster presentation with the title “Steel-Confined SiC Armour Against Oblique Penetration” at conference “29th International Symposium on Ballistics” organized by International Ballistics Society (IBS) in Scotland, Edinburgh, United Kingdom, May 9-13, 2016.

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