Physical protection:

Interdependence between hard armour and soft armour

A thesis submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

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Declaration

I, Rajneesh Jaitlee, certify that:

a. except where due acknowledgement has been made, the work is that of the candidate alone;
b. the work has not been submitted previously, in whole or in part, to qualify for any other academic award;
c. the content of the thesis is the result of work which has been carried out in the School of Fashion and Textiles, RMIT University and DMTC facilities;
d. any editorial work, paid or unpaid, carried out by a third party has been acknowledged;
e. ethics procedures and guidelines have been followed.

--------------------------------------
Rajneesh Jaitlee

31st. May 2013
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Dedication

This work is dedicated in memory of my maternal uncle

Late Mr. Vijay Kumar Pathak
Executive Summary

Commercial grade aramids like Kevlar® etc. have been used effectively in personal body armour systems, which are designed for physical protection and can also be designed in conjunction with hard armour plates (ceramics) depending on the severity of threat. The project emphasised the design and development of armour styles using new advanced material systems for physical protection comprising advanced textile substrates, ceramics, polymer composites and commercial-grade epoxy resins. Military personal body armour (PBA) systems normally consist of a hard armour plate (HAP) that functions as a strike face in front of a soft armour insert (SAI). In today’s world, high-strength composites that use fiber-reinforcing are often made of commercial aramids such as Kevlar®. These are embedded with ceramics which have high compression and hardness values. The advantages of these composite materials are high strength, high stiffness, reduced weight and design flexibility. In the past, armour manufacturers combined a variety of advanced commercial-grade aramids that could be used in conjunction with hard armour to select the best physical properties from the different material combinations. However, such systems provide very complex defence phenomena due to the interaction between the hard and soft armours within a very short time interval.

The aim of this research work was to study the interdependence between hard armour and soft armour systems by fabricating different armour styles and investigating their ballistic performance. The research work included improving the fabrication techniques used to for cladding the ceramic tiles for the existing armour systems and examining alternative design methodologies to reduce the Back Face Signature (BFS). One method was to apply tension on the cladding fabric covering the rear face of the ceramic tile. The research focus was complemented by mechanical testing as well as several series of ballistic tests. There were several important parameters considered, which included reduction in BFS value, weight reduction and enhanced flexibility of manufacture.

The research work undertaken in this study comprised of two sections- firstly, mechanical testing, and secondly, ballistic tests. Mechanical testing consisted of
investigating the physical characteristics of Kevlar® XP™, a non-crimp fabric from DuPont, by varying its orientation (discussed in detail in Chapter 3). Three series of three ballistic performance tests (Trial #1, Trial #2 and Trial #3) were conducted using Reaction-Sintered Silicon Carbide (RSSC) ceramic tiles of varying thickness as an initial strike face backed by a combination of laminated and/or loose Kevlar® XP™ backing materials (discussed in detail in Chapters 4—6). A range of armour styles was manufactured – identified as Basic Armour (BA), Optimum Armour (OP) and Standalone Armour (SA) using different batches of RSSC ceramic tiles with varying thicknesses (4 mm, 6 mm and 8 mm). The ballistic testing was conducted using single shot AK-47 ammunition, fired with a wide range of velocities, to understand the interdependence between hard and soft armours.

Trial #1 and Trial #2 comprised of 4 mm RSSC tiles used as an initial strike face during ballistic testing (more information in Chapters 4—5). The velocity range for conducting these ballistic tests was in the region of 520 m/s—620 m/s. For Trial #3 however, different thicknesses of RSSC tiles were used (4 mm, 6.5 mm and 8 mm) while conducting ballistic performance tests over an even wider velocity range 300 m/s to 1050 m/s (more information in Chapter 6). The BA armour style was the only the manufactured style common to all three ballistic trials (Trial #1, Trial #2 and Trial #3) and their results are evaluated in detail in Chapters 6—7. The modification of the cladding techniques for the RSSC tiles was also conducted in order to understand the effect on Back Face Signature (BFS) values.

It has been shown that by applying tension (in one direction only) to the Kevlar® cladding fabric across the rear face of the RSSC tiles, a reduction of 2.9 mm in the BFS values was observed. Evaluation and comparisons were also conducted between clad and unclad armour styles to understand the effects of cladding (more information in Chapters 6—7). However, the results showed that there was little difference in the BFS values observed between the clad and unclad armour styles. The ballistic tests confirmed that clad RSSC tiles do not fully disintegrate on the first impact when compared to unclad RSSC tiles.
**Nomenclature**

Armour: A material provided for ballistic defeat to oncoming projectiles or fragments when inherent shielding is inadequate.

Areal density: A measure of the weight of armour material per unit area, and expressed in grams per square metre (gsm).

Armour style: A complete armour system typically comprising of front clad ceramic tile, a backing laminate and several layers of soft vests. The armour style arrangements can vary and it may be a single style or consist of multiple parts that are worn around the torso, depending on the type of threat.

Ballistic impact: The impact caused due to hits on the armour style by projectiles, or other aerodynamically affected threat mechanisms.

Back Face Signature (BFS): The greatest extent of indentation into a supporting test material (e.g. Plastilina) caused by a non-perforating impact on the armour style (see Figure 4-14).

Backing material: The composite or other material used to back the ceramic strike face.

Ballistic limit: For a given projectile or bullet type, the velocity at which this projectile or bullet is expected to penetrate the armour 50% of the time. The ballistic limit is typically denoted the V-50 value.

Body armour: Personal protective equipment that provides protection for the body against specific types of ballistic threat. A body armour system would normally cover the torso but may also include the arms and legs as well as the sides of the torso, buttocks and groin.

Chronograph: An electronic instrument used to determine the time interval of projectile flight between two fixed measuring points.
Composite armour: An armour system consisting of two or more different armour materials, one of which is normally of a ceramic nature.

Complete penetration (CP): A complete penetration occurs when the impacting projectile, or bullet or any fragment of the test specimen such as a projectile etc. perforates the target.

Fracture toughness: One of the most important parameters of any material and is described as the ability of a material containing a crack to resist catastrophic failure.

Fragment Simulating Projectile (FSP): A projectile designed with special material, shape etc. and size for ballistic testing so that the effect of typical fragments can be simulated.

Hard armour or rigid armour: An armour system comprising of a rigid ceramic plate to provide physical protection against rifle threats

Initial velocity: The velocity of the projectile at which the projectile ceases to be acted on by propelling forces. For a gun-fired projectile the initial velocity, expressed as feet or metres per second, is also called 'muzzle velocity'

Supporting test material: A block of homogenous, non-hardening, oil-based modelling clay material placed in contact with the back of the armour style panel during ballistic testing.

Plate inserts: Hard armour plates or semi-rigid plates that are intended to be inserted into pockets of soft armour vests to provide increased physical protection against rifle threats.

Partial penetration (PP): An impact on the armour style or armour design which is not a complete penetration shall be considered a partial penetration.
Petalling: The plastic deformation of a ductile material when struck by an impacting projectile or fragment, resulting in material being forced outward in leaflets or petal forms.

Reference velocity: The measurement of velocity used for ballistic test rounds used in perforation-Back Face Signature.

Strike face: The surface of an armour designated by the manufacturer as the surface that should face the incoming projectile or external threat type.

Spalling: The delamination of a material layer in the area surrounding the location of impact, which may occur on either the front or rear surfaces of the armour.

Textile-based materials: Materials manufactured by weaving or felting yarns into a fabric, or by embedding or laminating fibers in sheets of plastic film.

V-50 ballistic limit: In general, the velocity at which the probability of penetration of an armour material is 50%.

*Note: the nomenclature has been taken from the reference [104].*
1. Introduction

1.1 History

There are many factors that have influenced the design and development of personal armour throughout human history. The design and development of personal armour runs parallel to the development of effective and efficient weapons, and aim to create better physical protection without sacrificing the safety and mobility of the wearer. The wearing of protective armour systems during combat has been known for centuries. In ancient times, unprocessed animal skins were used in combat applications, and then came leather, wooden and metals shield [1, 2]. During those times, soldiers wore breast plates made from heavy copper, iron and other materials. With the proliferation of different types of threat, and the advancement in warfare equipment, more advanced armour systems were developed and manufactured; however, they were heavier, restricted mobility and were burdensome to the wearer [1].

The use of leather caps and helmets around 2800 BC was favoured by the Sumerians [3]. Around 1100—600 BC the Assyrians were considered the most advanced and sophisticated among the ancients for their armour [3]. During the 14th and 16th centuries AD the weight and thickness of the armour was of paramount concern. Weights varied from 15 kg to 25 kg, although they provided substantial resistance to the penetrating weapons. In the early 15th century, due to the invention of firearms and a broadened range of threat, metal body armour became ineffective. However, during the American Civil War the dynamics of the battlefield changed significantly for soldiers [4].

In 1880, Ned Kelly, an Australian bushranger, made armour from plough blades as shown in Figure 1-1. The armour, having a mass of around 44 kg, covered the torso and upper legs, and was worn with a helmet [5]. The armour endured many rifle bullet hits with none penetrating, but eventually proved to be ineffective as the ballistic suit lacked protection for the legs and hands, and was a burden to the wearer [5].
With the advancement in technology, different materials such as steel were used for armour protection. Products like breast plates made from these materials although providing protection were heavy and restricted the mobility of the solider. The first modern armoured tank with flat-rolled steel plate appeared during the First World War [3]. In the First and Second World Wars, knowledge about personal protection was limited for the average soldier. It was the French, German and British armies that used breast plate protection during the First World War [4]. Many countries during this time developed various forms of personal protective devices for the torso and the extremities; however, due to their excessive weight and lack of personal protection, their use was restricted [6].

A casualty study analysed by British forces indicated that more than three-quarters of wounded men could have been saved if a minimal form of adequate personal protective armour system had been worn [6]. Similarly, a casualty study analysis conducted by French forces indicated that 60% to 80% of wounds were produced by projectiles of low to medium velocities [6]. It was during the Vietnam War that soldiers began to routinely wear ballistic vests using ceramics to protect themselves from extreme projectile threats [1]. During this era, flat jackets were used as protection; however, they provided limited protection against high speed projectiles [4].

Figure 1-1: Ned Kelly's ballistic suit
During the Second World War tanks used by the Germans and Soviets had thick steel plates of 150 mm and 75 mm respectively. However due to technology advancement especially in manufacturing techniques, there was also improvement in the armour systems and this is illustrated clearly in Figure 1-2 [7]. It was in the 1950s that the Americans started using aluminium as an armour grade material in armoured vehicles [8]. In 1963, Goodyear Aerospace Corporation designed an armour that performed equivalent to rolled homogeneous armour (RHA) with its weight reduced to half [8].

Figure 1-2 depicts the performance timeframe of armour systems development over ten decades [7]. Initially during the early 1900s, heavy steel plates were used in tanks. With advanced processing techniques came the introduction of lightweight materials. Materials like ceramics have been used for personal protection since the mid-1900s often in conjunction with composites. Currently, different alloys, along with transparent ceramics, are used in armour systems for personal protection.

With technological advancements in research and development of new materials, along with new techniques for manufacturing ceramics, new armour-grade materials and systems were initiated using aluminium oxide, silicon carbide and boron carbide. Figure 1-3 represents the areal density of armour systems that were required to defeat 7.62 mm armour-piercing (AP) projectiles. It also
represents the improvements in efficient ballistic armour systems where metals and aramids were developed for use in conjunction with backing materials (e.g. textiles) [8].

Figure 1-3: Areal density of armour needed to stop 7.62 mm AP projectiles [8]

In recent decades, high-performance fibers and ceramics have resulted in the significant advancement of body armour systems [8]. The weight is of paramount consideration when designing body armour systems that are subject to impulsive loading conditions [8]. Military standards are now used to rate the efficiency and effectiveness of personal body armour (PBA) systems. These standards are used to evaluate typical material properties and target deformation after being impacted. It is a common practice for both military and civilians to assess the performance of personal body armour systems by applying active standard National Institute of Justice (NIJ) 0108.01 Level, as represented in Table 1-1.
The ballistic vest is a personal body armour system (PBA) that helps absorb the impact from external threat types and is worn on the upper torso. Ideally, the PBA designed for personal protection should be efficient, effective and lightweight. PBA systems that are designed to defeat high-velocity rifle rounds normally consist of a hard armour plate (HAP) that functions as an initial “strike plate” in front of a soft armour insert (SAI). Depending on the severity of the threat type, the PBA can be used with or without the HAP; however, when used together, the performance of the HAP relies on support from the SAI. The usual parameter for SAI is the emphasis on how many layers of woven or laminated fibers are capable of protecting the wearer for the designated threat type.

There are many vital parameters that need to be considered while designing and testing ballistic armour, for example understanding the penetration mechanism, the design and development stages depending on threat type, including comfort, weight and multi-hit properties, and the need for long-term maintenance to ensure a minimum level of performance reliability. These vital factors are important considerations for decisions about its application in the field. Therefore, rigorous research about soldiers’ psychology and practical life experience with PBA systems is vital in order to determine its overall protective armour efficiency and performance.

During the past few decades, researchers in various countries and industries have conducted their research work on different commercially-available ballistic materials and their interaction with high-velocity projectiles or extreme types of
threat [4]. Figure 1-4 presents the relationship between the probability of penetration vs. velocity. The region (A) within the sigmoidal curve highlights the arrest of the projectile; region (B) depicts the velocity range within which the probability of perforation rapidly increases, and region (C) shows the situation for complete penetration [8].

![Figure 1-4: Probability curve for perforation vs. velocity [8]](image)

1.2 Aramid and ballistic fibers

The word aramid is a generic term used for manufactured fiber where the fiber forming substance is comprised of a long chain of synthetic polyamide compound that has at least 85% of its amide linkages attached to two aromatic rings [9]. The diameter of these fibers is very small and is spun from spinnerets as group of parallel filaments. These filaments that form the basis of both woven and non-woven ballistic fabrics include Kevlar® 29, Kevlar® 129, Twaron®, etc. Figure 1-5 shows the chemical structure of the para-aramid fibers. This chemical structural arrangement allows fibers to have a high tensile strength and high modulus structure [1].

![Figure 1-5: Chemical structure arrangement of para-aramid fibers [1]](image)
During the mid-1960s, the man-made fibers nylon and polyester were in high demand since they had maximum tenacity (breaking strength) and modulus [10]. Nylon has a high strength-to-weight ratio and fabrics made from it could be fashioned in sufficient layers to prevent penetration of many sharp-extremity threats [1]. DuPont scientists in the mid-1960s and 1970s discovered a new technique for producing a perfect extension for polymer chains by developing a family of fibers nearly three times stronger [10]. These fibers were stronger than nylon with higher modulus and were tougher and lighter than fiberglass. This fiber was later commercialised as Kevlar® 29 [4]. During 1986, another typical commercial aramid, Teijin – Twaron® was also introduced commercially into the market [1].

Ballistic fibers are man-made fibers that possess properties such as high tensile strength and high modulus with low fiber elongation and resistance to chemicals [4]. These fibers are fabricated using a unique spinning technique and their tensile properties are determined by their structural characteristics [4].

In the early 1970, the development of lightweight fiber-reinforced armour systems with different weave structures was coupled with a variety of commercial grade resins under different curing conditions (heat and pressure) [4]. Ultra-high molecular weight polyethylene (UHMWPE) was introduced in the mid-1980s, followed by PBO in the late 1990s. UHMWPE consist of long chains of polyethylene, as shown in Figure 1-6, and these fibers are generally 10 times stronger than steel. UHMWPE fibers possess non-linear visco-elastic properties.

![Structure of UHMWPE](image)

**Figure 1-6: Structure of UHMWPE [11]**

PBO is the abbreviation for poly (p-phenylene-2, 6-benzobisoxazole), a rigid, isotropic polymer and the strongest synthetic polymer, as shown in Figure 1-7. PBO is a liquid crystal polymer developed by Toyobo under the trade name
Zylon®. PBO possesses desirable properties of high thermal stability with low creep and has excellent resistance to stretch after repeated folding. PBO is also flexible and has a soft feel, although PBO has poor resistance to both UV and visible light. PBO provides excellent mechanical properties paired with extreme thermal stability and because of this PBO is the optimum material for applications such as for lightweight bulletproof vests [12]. Over recent years however, these fibers have been shown to degrade quite severely under conditions of extreme humidity and temperature [13]. Table 1-2 shows a comparison of different high-performance ballistic fibers [4].

![PBO structure](image)

Figure 1-7: PBO structure [1]

Due to developments in technologies like production, fabrication, weaving techniques, etc. a new range of high-performance ballistic fabrics came onto the commercial market with 0° and 90° mix and match orientations. This allowed enhancement in the dynamics of lightweight armour, resulting in weight reductions of about 10—20% achievable every decade [4]. The mechanical properties of these high-performance commercial-grade fibers are compared and illustrated in Figure 1-8.

*Note: tenacity represents the strength of the yarn or the force required to break the yarn and is denoted grams per denier (G/D). The terms LM, HM, AS represent Low Modulus, High Modulus and As Spun respectively.*
1.2.1 Kevlar®

Kevlar®, an organic fiber in the aromatic polyamide family, was commercialized as an industrial fiber in 1972 [9]. Kevlar® fiber has a high strength and high modulus as compared to other commercially available man-made fibers [10]. Kevlar® aramid fiber has a higher breaking tenacity as compared to steel wire, polyester yarn, and nylon. Kevlar® has a lower elongation at break (refer to Table 1-2), and has a lower density than steel and glass [9]. Extruded Kevlar® filament is one of the most common synthetic fibers used in ballistic protective applications [9].

Kevlar® is similar in structure to Nylon-6, 6 except that instead of the amide links joining chains of carbon atoms together, they join benzene rings. The two monomers are benzene-1, 4-dicarboxylic acid and 1, 4-diaminobenzene as shown in Figure 1-9. If these molecules are lined up and a water molecule between the
-COOH and -NH₂ groups is removed, the structure of Kevlar® results, as shown in Figure 1-10.

![Diagram of benzene-1,4-dicarboxylic acid and 1,4-diaminobenzene]

Figure 1-9: Molecular structure of benzene-1, 4-dicarboxylic acid and 1, 4-diaminobenzene [9]

Kevlar® is an extremely light but strong (about five times as strong as steel) synthetic fiber and its development has advanced material science, particularly in the areas of fiber-reinforced composites and ballistic applications. Parallel bundles of filaments are formed as yarns with no twist, and are usually woven to form the fabric. The density of yarns and tightness of the weave structure can be varied depending on the threat type for ballistic applications.

### 1.2.2 Kevlar® XP™

Kevlar® XP™, a recent innovation fabric from DuPont™, can be used to create NIJ Level IIIA vest designs that provide superior ballistic performance and can reduce Back Face Signatures (BFS) by approximately 15% or more, over other designs [14] The Kevlar® XP™ fabric technology enables vests to weigh at least 10% less than those made with other commercially-available technologies, while still being made of Kevlar® material [15].

The Kevlar® XP™ fabric is constructed by aligning flat tapes of parallel Kevlar® filaments to form one side of the fabric, with the second layer of Kevlar® on the other side, oriented at 90° to the first. There is an intervening bonding layer holding these filament layers in place. Figure 1-11 represents a
schematic of the 90° pattern of Kevlar® filaments on the front and back faces of a single layer of Kevlar ® XP™ fabric. The Kevlar® XP™ fabric is sewn together with parallel lines of sewing 5mm apart, which cut through the two Kevlar® layers at 45° The Kevlar® XP™ is coated with a resin during its fabrication process and the lines of sewing merely hold the structure in place during manufacture. The strength of the sewing thread is not intended to provide any significant additional ballistic strength. In the current research work, Kevlar® XP™ is used as the backing material in various forms of laminates (as discussed in Chapter 4) to form various composite panel assemblies/laminates.

1.2.3 Linear Low-Density Polyethylene (LLDPE)

Linear Low-Density Polyethylene (LLDPE) is produced at lower temperatures and pressures, by co-polymerisation of ethylene and higher-alpha olefins [16] LLDPE is a linear polymer (polyethylene) with significant numbers of short branches and constructed via co-polymerisation of ethylene with longer-chain olefins [16]. The linearity of LLDPE results from the different manufacturing processes used for LLDPE and Linear Density Polyethylene (LDPE) [16] LLDPE polymer has a narrower molecular weight distribution than conventional LDPE and, in combination with its linear structure, significantly different rheological properties [16] Due to its narrower molecular weight distribution, it is less shear resistant [16] The lower shear sensitivity of LLDPE allows for a faster stress relaxation of the polymer chains. During shearing failure LLDPE remains more viscous and can be used in ballistic applications to provide a mechanism for impact penetration. During melt extension, LLDPE has lower viscosity at all strain rates. Other important parameters of LLDPE include high
tensile strength and resistance to puncture. LLDPE is very flexible and generally elongates under stress conditions. It can also be made into thin films.

In this current research work, LLDPE was used as a thin film application to provide a thermoplastic matrix to bond, under appropriate temperatures and pressures, adjacent Kevlar® XP™ layers, to form a variety of composite panel assemblies/laminates (as discussed in Chapter 4).

1.3 Ceramics

Ceramics possess high hardness, high flexural modulus with low fracture toughness but they are brittle in nature. Due to their low bulk density, they have excellent specific properties such as high compressive strength. They are structurally stiff and have a high rate of energy absorption with light weight as compared to the equivalent properties of metals. Because of their mechanical properties, they are used as the initial strike face for the ballistic panel (i.e. they are the primary material that faces the impacting projectile).

Silicon carbide (SiC) and boron carbide (B₄C) are two typical examples of ceramics used as strike faces in ballistic applications (see Table 1-3). When impacted by a projectile, ultra-hard ceramics are capable of dissipating most of the energy by deforming or abrading the projectile. Ceramic material such as silicon carbide exhibit performance variability under high dynamic loading [17]. In the current research work, a silicon carbide ceramic is used as the strike face in combination with a high-strength backing material that can cause erosion and deform the projectile. When a brittle material such as a ceramic is subjected to quasi-static loading conditions, tensile failure will be initiated by stress concentration [17].
Table 1-3: Typical properties of ballistic ceramics [18]

<table>
<thead>
<tr>
<th>Ceramics</th>
<th>Density (g/cm³)</th>
<th>Elastic modulus (GPa)</th>
<th>Flexural strength (MPa)</th>
<th>Vickers hardness (GPa)</th>
<th>Fracture toughness (MPa.m²/²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>3.8</td>
<td>340</td>
<td>400</td>
<td>14-18</td>
<td>2.8-4.5</td>
</tr>
<tr>
<td>B₄C</td>
<td>2.5</td>
<td>400-450</td>
<td>400-500</td>
<td>28-32</td>
<td>2.5-3.0</td>
</tr>
<tr>
<td>SiC</td>
<td>3.2</td>
<td>350-470</td>
<td>350-700</td>
<td>22-26</td>
<td>2.8-4.3</td>
</tr>
<tr>
<td>TiB₂</td>
<td>4.5</td>
<td>540-570</td>
<td>260-280</td>
<td>21-26</td>
<td>5.4-6.9</td>
</tr>
<tr>
<td>Si₃B₄</td>
<td>3.2</td>
<td>310</td>
<td>800-1000</td>
<td>17-18</td>
<td>5.0-6.0</td>
</tr>
</tbody>
</table>

1.3.1 Silicon carbide (SiC)

Grains of silicon and carbon can be bonded together by sintering to form a very hard ceramic. SiC ceramics have been manufactured by the reaction sintering process, which involves the infusion of liquid silicon into a porous ceramic preform. This may lead to a number of characteristic, casting-like defects such as a) islands of free silicon metal, b) small, closed areas of un-sintered material, c) conventional porosity. The SiC composition indicates that the SiC content will be about 88%, since there is about 12% of residual silicon in these products.

Ceramics possess the superior properties of low density, high elastic modulus and high strength [19]. On the other hand, ceramics have low toughness, high brittleness and a low coefficient of thermal expansion [19]. The mechanical properties of SiC such as density fall between those of Al₂O₃ and B₄C. SiC is manufactured either by pressure-less sintering or reaction sintering and a reaction-bonded mechanism. The ballistic properties of these ceramics do not depend on individual mechanical parameters but depends on a range of mechanical properties [18].

The microstructure of a ceramic tile and its ability to dissipate energy during the interaction with a projectile’s can have significant effects on ballistic performance. The ballistic energy dissipation also depends on the phase composition and structure of ceramics [20]. Figure 1-12 shows the microstructure within some ceramics [21]. Grain size, grain boundary and microstructure can affect ballistic properties of the ceramics [21]. Fine-grained ceramics are mechanically stronger than coarse-grained structures. Figure
1-12(a) represents a single-phase ceramic along with voids within its grain structure. The microstructures of the resin-bonded ceramics are shown in Figure 1-12(b). The microstructure may be in single-phase with precipitates of the second-phase as shown in Figure 1-12(c). The microstructure of a ceramic that has more than one phase can be seen in Figure 1-12(d) [21]. Figure 1-13 and Figure 1-14 represent a comparison between various materials in terms of hardness, specific gravity and compressive strength [21].

![Microstructures of ceramic materials](image)

Figure 1-12: Microstructures of ceramic materials [21]

![Tensile and compressive strength of different materials](image)

Figure 1-13: Tensile and compressive strength of different materials [21]

### 1.3.1.1 Reaction-sintered silicon carbide (RSSC)

Reaction-sintered silicon carbide (RSSC) is made by infusing a porous green body of silicon carbide and carbon powders with liquid silicon. The silicon reacts with the carbon to form secondary silicon carbide on the primary silicon carbide grains. This results in an almost pore-free microstructure, with the
excess silicon filling the residual pores. RSSC ceramics tiles for armour applications are regularly x-rayed or non-destructively inspected to ensure integrity of structure and, impact/ballistic performance. Many casting-like defects may occur during the high-temperature process as the liquid silicon infiltrates the green compact.

![Fracture toughness, modulus of elasticity and hardness comparisons of different materials](image)

Figure 1-14: Fracture toughness, modulus of elasticity and hardness comparisons of different materials [21]

### 1.4 Fiber-reinforced polymer

Fiber-reinforced polymer is a composite material made up from a polymer matrix reinforced with fibers such as aramids and also comprised of different grade resin systems. The fiber-reinforced polymer acts as a composite material with significantly different physical or chemical properties. The advantage of fiber-reinforced polymer is that it is strong with high fracture toughness and low density and provides flexibility to the end-user. For armour designers, the fiber-reinforced matrix also provides flexibility against different types of threats.
The strengthening of a fiber-reinforced system may only occur when the elastic modulus of the fibers is greater than that of the matrix, as studied by Donal et al. (1976). The study found that when fibers of low modulus are used, the ultimate failure stress will be reduced because, instead of the fibers, the matrix will carry the applied load.

1.5 Current research

In this current research work, reaction sintered silicon carbide (RSSC) tiles clad with high strength aramid fabrics were used as an initial strike face. The RSSC tiles were clad using a commercial epoxy resin to bond the backing material Kevlar® XP™ to form different compositions (laminate or soft layers) for different armour styles (as discussed in Chapter 4). A series of different clad armour styles was manufactured and later tested for ballistic performance against AK-47 projectiles (NIJ-01.01.04 Level-III) over a range of impact velocities to understand their penetration and failure mechanisms. Mechanical tensile tests on Kevlar® woven fabrics and Kevlar® XP™ in various orientations and with different RSSC combinations were also conducted to understand their failure mechanisms. These tests were complemented by optical microscopy and scanning electron microscopy (SEM).

The research also placed emphasis on the single-shot ballistic test of unclad tiles to understand and compare their failure and penetration mechanisms with those of clad tiles. This allowed the effects of cladding to be examined. After penetration of the ceramic strike face, residual energy from the projectile was subsequently absorbed by layers of high-strength, high-modulus aramid placed behind either as a bonded backing laminate or as individuals layers (or some combinations of both) using Kevlar® XP™ and layers of LLDPE. The details of these clad and unclad armour styles manufactured will be discussed in detail in Chapters 4—7.

Note: due to the proprietary nature of the project, and IP information, the name of the commercial epoxy resin used cannot be disclosed. The cladding
technique i.e. the way cladding was bonded to the front and rear faces of the RSSC tiles cannot be disclosed for the same reason.

1.6 Aims and objectives

The aim of this research work is to investigate the interaction between soft and hard armour styles and to determine their interdependence. From an engineering viewpoint, evaluation and analysis of the performance of these armour styles were conducted by carrying out ballistic tests which aimed to lead to an improved performance.

The detailed objectives of the current research work undertaken are:

- manufacture armour styles in different configurations for ballistic tests using commercially available materials
- create a benchmark for mechanical testing under different orientations
- create a benchmark for ballistic testing for armour style to be manufactured in the future
- compare Back Face Signatures (BFS) for different manufactured and ballistically tested armour styles
- understand and identify the mechanisms of energy dissipation
- study the cone angle formation with different RSSC tile thicknesses at comparable velocities
- understand radial and circumferential crack patterns emanating from the point of impact
- evaluate the post ballistic test analysis on the armour styles
- understand and evaluate the effects of cladding on RSSC tiles.

Note: in this research work, no hypothesis was directly mentioned. The intention of this research was to investigate the interactions between various components that constituted a typical ballistic vest, and consider ways of improving performance
2 Literature Review

2.1 Introduction

Ideally an armour system designed for personal protection should be effective and lightweight. Military personal body armour (PBA) systems normally consist of a hard armour plate (HAP) that functions as a strike face in front of a soft armour insert (SAI). The performance of the HAP relies on support from the SAI. The PBA is a complex armour system that is widely used in personal ballistic armour applications where the HAP (often in the shape of a ceramic tile) is used to deform or erode the projectile during the ballistic impact and the SAI – usually based on an aramid textile arranged in different compositions such as soft vest layers or as laminates-absorbs the remaining energy from the projectile. In this research work, silicon carbide (SiC) has been used as the ceramic strike face backed up by different compositions of laminate or soft vest layers (more details in Chapter 3) with similar areal density (AD).

2.2 Ceramic armour system

Ceramic-faced armour system failure mechanisms have been widely studied [22-25]. There are several physical parameters and material properties that are involved during complex ballistic penetrations such as velocity of projectiles at impact, hardness and ergonomics of projectiles, rigidity and strength of the backing laminate, thicknesses, etc. Ceramic properties such as high hardness, high Young’s modulus, low Poisson’s ratio, low density and low porosity that influence the performance of armour ceramics [26]. Due to its high hardness value and high compressive strength the primary aim of the ceramic plate is to mushroom, breakup and erode the tip of the projectile. The ceramic also assists in dissipating the kinetic energy (KE) of projectiles over a larger surface area of the backing material during conoid formation [27]. The impact from the projectile generates compressive shock waves that travel across the ceramic thickness to cause the formation of the cone angle within the ceramic. This reduces the local pressure on the backing laminate or soft vest layers by spreading the energy from the projectile over a wider area. The backing material and soft vest subsequently absorb the remaining kinetic energy of the projectile.
The failure mechanism within armour systems have been widely studied [28, 29]. It also highlights the in-depth knowledge and explanations of penetration mechanisms on the strike face (i.e. ceramics) and the interactions between the projectile and the strike face in conjunction with the backing materials. The initial damage to the ceramics as initiated at a localised region where the projectile impacts on the impacting surfaces [30]. This localised region cause fractures to spread across to form coaxial cylindrical cracks or Hertzian cracks as shown in Figure 2-1. These cracks coalesce into a conoid that intersects with the backing material.

Figure 2-1: Hertizan crack formation due to the ceramic strike face interacting with the projectile [27]

The comminuted region during projectile ceramic interaction has been researched by many authors [23, 31-33]. The study was also conducted to determine the properties of SiC granular ceramics during projectile-ceramic interaction [34]. The behavior modelling of pulverized ceramics and the dynamic behavior SiC for symmetrical plate impact techniques were also studied [35, 36] During the projectile ceramic-interaction, fracturing of the ceramic rubble results in radial tensile stresses that cause formation of radial cracks. These radial cracks cause a rise in the three-dimensional stress phenomenon [24]. In general, ceramic pulverization occurs from the formation of relatively large fragments that fracture, resulting in turn in smaller fragments. Indeed, it has also been mentioned that in order to improve the ballistic efficiency of the armour system, the time required to accomplish complete ceramic comminution by the projectile should be increased [24].
Hertz [37] studied cone cracking in detail. Wilkins et al. [22, 28, 38] studied the failure mechanisms of projectile penetration with thick ceramic plates. The study found, cracks formed by cone angle formation have been considered the major damage mechanism. Finite element analysis (FEA) was conducted to understand the cone cracking failure mechanism, in order to identify the cone angle formation and nucleate damage caused by impact analysis [39-42]. The failure mechanism for thin ceramic plates where the cone contains radial cracks [41]. However, for thinner ceramic tiles, where the thickness is comparable to the projectile diameter, radial cracks are usually observed as the major damage mechanism [41, 43, 44] but this is mostly ignored. Ceramic plate thickness plays a vital and fundamental role in the reduction or loss of the ballistic impact energy as studied by [45]. Experimental results demonstrate that by increasing the grain size of the ceramic (aluminium oxide), it is possible to considerably improve armour efficiency without increasing the ceramic thickness [45].

During the impact interaction, the stresses are mainly compressive and the ceramic will initially deform in an elastic manner [27]. During the impact, the front face of ceramic is under compression and the rear face is under tension. On the front face, of the ceramic radial tensile stresses are generated which lead to the formation of one or more Hertzian cracks as shown in Figure 2-1. These cracks originate as circular or radial cracks normal to the surface at the periphery of impact point and then propagate into the ceramic at an angle of 15—65° to the surface (shear) to form conoid. This angle of the fracture conoid depends on the dynamic loading conditions within the ceramic material. Elastic waves produced by the initial impact will reflect from the rear surface and edges of the ceramic tile as tensile waves and may cause additional fracturing. Flexing of the backing layer, and ceramic leads to the formation and distribution of radial cracks, which spread away from the impact point towards the ceramic boundaries.

Depending on the projectile velocity, some of the kinetic energy of the projectile is dissipated by deformation and damage mechanisms within the backing layers. Numerous analytical models have also been studied for the penetration mechanism for two-component composite armours comprising a ceramic front
plate and ductile backing laminate. These armours offer lightweight and high ballistic performance as studied [46-49]. Composites made from a ceramic-fiber matrix demonstrated a high capability after ballistic impact due to the combination of high compressive strength properties of the ceramics and their ability to dissipate impact energy [50]. Fiber-reinforced plastic composites are frequently used to their low density, high strength and strain energy to failure [51]. For ballistic protection, different types of ceramic materials are commonly used; including some oxide ceramics like alumina and non-oxide ceramics like, carbides, nitrides, etc. [50, 52-54].

2.2.1 Impact behavior of ceramics

Several published penetration failures of ceramic tiles have been studied [55, 56]. In general, the impact response is influenced by bulk properties, such as elastic moduli and bulk modulus, which determine the spread of energy during impact conditions. However, compressive strength is considered the vital property within ceramics to prevent penetration. During impact conditions, tensile stresses are experienced by materials after extreme compressive loading. The impact failure mechanism occurs at a comparative short time interval, such that different sections of the ceramics cannot interfere with other section.

The initial phase of impact on the ceramic consists of the shock phase, where shock stresses are extremely high, as shown in Figure 2-2. The primary failure mechanism in ceramic tiles is the tensile failure on the back surface opposite to the point of impact. The tensile stresses developed inside the ceramic after the initial shock are due to hoop stresses behind the shock wave and the reflection of the compressive wave as tensile waves at the boundary of the tile. It is therefore the high stresses that are generated during impact that cause the ceramic breakdown in the front of the penetrator during impact phase, results in ceramic failure ahead of the projectile.
Impact of projectiles on the ceramic-faced armour was classified into two time response periods [58], i.e. the shock wave period and structural response period. During the shock wave period, for a few microseconds, limited stress wave reflection occurs across the armour plate. It is during this period when the shock degradation of the armour occurs by micro fracture, caused due to a high pressure wave followed by a rarefaction wave through the ceramic, resulting in eroding or deforming of the projectile. During impact, high stress waves are produced in the projectile, causing radial expansion and erosion of the projectile tip. The degrees of this shock degradation and projectile erosion depend on the initial shock wave and resulting refraction wave energy. The damage in the ceramic is influenced by the shocks induced above the Hugoniot elastic limit (HEL) [57]. In general, for ceramics, fracture starts to spread in the material instead of the projectile. The initial damage in the ceramic initiates at the point projectile impact. It is from this point of contact where the formation of radial and circumferential cracks starts and forms a conoid that intersects with the back plate.

The structural integrity of the system can be classified when the armour is completely penetrated (CP) or the projectile has partially penetrated (PP).
the penetration, the projectile makes an effort to penetrate pulverised or powdered ceramic. Depending on the resistance from the ceramic material, erosion or deformation of the projectile occurs. During penetration, the fractured ceramic is pushed away by the projectile through the impact hole. The impact from the projectile causes the formation of a ceramic conoid, which distributes the energy over the larger area of the back plate that deflects under the applied load, causing the pulverised ceramic to move, as shown in Figure 2-3. As the progression of the projectile continues, the back plate dissipates the energy by plastic deformation. Depending on the mechanical properties of the back plate, once the back plate reaches its energy absorption limit, failure tends to occur by either plug shearing or strain failure, as shown in Figure 2-3. [3]

Figure 2-3: Penetration phases of armour [3]

For ceramic-faced armour to defeat a projectile, the mass erosion of the projectile is a vital mechanism. The initial stage of projectile energy is consumed by eroding or deforming the projectile, rather than the energy being absorbed by the armour, as indicated in Figure 2-4. The back plate generally absorbed up to 60% of the energy from the projectile.

Fracture of the ceramic material is an important mechanism that cannot be ignored. The time interval required for this fracture can have significant effects on the erosion or deformation of the projectile mass. During the ceramic fracturing process, a negligible amount of kinetic energy from the projectile is
dissipated [53, 56]. Cline et al. [38] showed that deferring the fracture by two micro-seconds can result in better armour due to projectile erosion.

2.3 Cladding of ceramics

Often in ceramic-faced armour systems, high-strength resin bonding is used to bond the ceramic tile to the backing material [59]. The armour system also includes a spall shield of a single layer of polymer composite on the front face of the ceramic tile. The combined effect of the spall shield and backing is to constrain the radial and circumferential cracks formed in the ceramic tile and so prevent them from opening. The damage caused to ceramics is generally augmented by any pre-existing defects within the ceramics that are caused due to shear and during impact by tensile forces [60]. The efficiency of the ceramic is to increasing the time interval during which the ceramic interacts with the projectile before it deforms increasing the dwell time.

The cladding on the armour front face (the strike face that is first to encounter the ballistic threat) has little implication for the ballistic performance compared to the cladding on the back face [61]. Wrapping of the ceramic material is the simplest and easiest mechanism, providing improvement in the performance in the body armour, by using a layer of fiberglass (prepreg). The prepreg methodology was applied in the current research to the majority of materials tested for ballistic performance. When the wrapping of armour ceramic material

Figure 2-4: Steel projectile impacting armour (Energy v/s Time) [3]
was employed, the pulverizing of the ceramics and associated formation of a fine ceramic powder were significantly less, causing more erosion to the projectiles. The encapsulation of the ceramic plates, using 0.5—1mm thin polyethylene or, especially, a polyurethane layer, resulted in a significant improvement ballistic performance [62] Thus the use of a thin polyurethane layer reduced the perforation of the Kevlar® backing for alumina ceramic body armour plates about two times with shooting using NATO Ball and LPS ammunition, i.e. the amount of the backing plies may be reduced.

2.4 Florence -projectile armour interaction analysis

Florence studied the sequence of events that occurs when a projectile strikes a ceramic face of a composite armour [29]. The study specifies that when the projectile hits a ceramic material, its tip is deformed, because the radial and circumferential tensile stresses exceed the fracture stress at the tip of the projectile. Due to the deforming failure mechanism, this causes projectile deformation and increases the surface contact area of the interaction with the ceramic, resulting in the spreading of the load and increased energy absorption.

A small region of fine ceramic cracking occurs due to the radial expansion of large tensile stresses from the point of impact, causing the pulverized ceramic powder to be ejected in the direction opposite to that of the impact. On the face opposite to the impact, a radial cracking zone develops because of the expansion of the tensile stress field. This result in a variation in the density of cracking that falls away from the point of impact and is primarily confined to a conoidal shaped volume. The defeated mushroomed projectile that remains, along with the broken ceramic material exerts pressure on the textile (aramid) material, backing which absorbs the remaining kinetic energy (KE) of the projectile by bending and stretching [29].
2.4.1 Florence analytical model

Analytical analysis conducted by Florence [29] specifies that the impactor was modelled as a short cylindrical rod that strikes the ceramic plate, as shown in Figure 2-5. The tip of the impactor shatters and the ceramic plate breaks progressively into a fractured cone of material, as outlined earlier. The impact energy is transferred to the backing laminate, which deforms like a uniform membrane. The Florence model also specifies the limitations that arise from the mechanical properties of ceramics and energy dissipation during the fracture of the ceramic [29].

Before impact, the kinetic energy (KE) of the projectile can be calculated using the formula in Equation 2-1 [29]:

\[
KE = \frac{1}{2} M_p \ V_p^2 \quad \text{Equation 2-1}
\]

where,

KE = kinetic energy of projectile before impact

M_p = mass of projectile

V_p = velocity of projectile

The velocity distribution of the projectile is evaluated by momentum conservation and the maximum strain (\(\varepsilon_r\)) can be calculated using the formula in [29]:

---

Figure 2-5: Schematic of two-component armour system [29]
\[ \varepsilon_r = 1.82 \; f \; a \; \frac{K}{S} \]  

Equation 2-2

where,

\( f(a) \) = simple ratio

\( S \) = constant tension in membrane (backing)

Constant tension in the membrane (\( S \)) value can be calculated using the formula in Equation 2-3 [29]:

\[ S = \sigma \; h_m \]  

Equation 2-3

where,

\( \sigma \) = yield stress of backing

\( h_m \) = backing thickness

The simple ratio \( f(a) \) can be calculated using the formula in Equation 2-4 [29]:

\[ f(a) = \frac{M_p}{M_p + m_c + m_m \; \pi a^2 \; \pi a^2} \]  

Equation 2-4

where,

\( M_p \)= mass of projectile

\( m_c \)= mass per unit area of ceramic

\( m_m \)= backing mass per unit area

\( a \) = conoid base radius (i.e. \( a = a_p + 2 \; h_c \))

Lastly, the ballistic limit (\( V_p \)) can be determined using the maximum strain (\( \varepsilon_r \)) failure criterion and can be calculated using Equation 2-5:

\[ V_p = \varepsilon_r \; [S/0.91] \; M_p \; f(a) \; \frac{1}{2} \]  

Equation 2-5

2.4.2 Stress wave propagation

Figure 2-6 and Figure 2-7 represent the principal planes within the impacting projectile and the impacted ceramic, where the maximum tensile stress exceeds 7 kbar, as represented by lines and dots [29]. The figure represents the elastic behavior of the material. The stress component acts perpendicular to the lines shows in Figure 2-6 that represent an axisymmetric fracture pattern. The stress
component acts perpendicular to the meridional plane, as shown in Figure 2-7 that represents a radial cracking [29].

Figure 2-6: Principal tensile stress [29]

Figure 2-7: Hoop stress locations [29]

Note: hoop stress in a material is defined as the circumferential stress subjected to both internal and external pressure.
2.5 Penetration failure mechanisms

The interaction of the projectile and armour is a complex phenomenon and several failure mechanisms occur during the micro-second impact time interval. In order to understand these failure mechanisms, it is useful to understand each failure mode individually. During the interaction, some important parameters to consider for armour are the strike face (ceramic or metal), bending resistance, strength, density and thickness, as illustrated by Wilkins [22]. Similarly, from the perspective of the projectile, some important parameters that need to be considered are the high velocity, the profile of the projectile, impacting conditions etc. High moduli and high shear strength characteristics of the material are responsible for resisting deformation, and bulk modulus and shear moduli are responsible for resisting the bending mechanisms [22].

During impact, two types of material failure mechanism are observed. The initial failure mechanism is observed when the elastic limit exceeds the plastic flow occurs. When the cohesive force of the material is exceeded, fracture failure is observed. During complete penetration of the ceramic armour, failure of the material occurs due to fracture. The changing shape of the projectile face has an influence on the failure mode during the failure interaction. According to Wilkins [22], there are other important parameters that need to be considered during penetration phenomenon – thickness of the plate (δ) and radius of the projectile (r). The plate is considered thick if the ratio of δ/r >1 and thin if the ratio of δ/r <1. However, if the ratio of δ/r is too small, failure occurs from in-plane stress. [22]

Wilkins [22] has demonstrated that a combination of two or more mechanisms results in complete penetration of an armour. These main failure mechanisms are spall, petalling, plugging and hole enlargement by the effects of radial flow. The plugging or petalling failure mechanism is dependent on the material properties of the impact face and the geometry of the projectile. A plugging failure mode corresponds to thick ceramics and a petalling failure mode is initiated in thin ceramics. However, if the ratio of δ/r =1, the failure mechanism can be due to either plugging or petalling. Spall failure is the first failure to occur
within the armour due to a combination of stress and strain, and the failure mechanism occurs in those regions where there is high tensile stress and low strain. A plugging failure mechanism occurs where the rate of heat generated during plastic deformation is more than the heat dissipated by conduction. In this case, the temperature is increased locally at the failure zone, resulting in reduced material flow stress. A petalling failure mechanism is observed where the fracture is initiated on the axis, through the thickness of the plate, resulting in petal formation.

Figure 2-8 represents an ogive tip steel projectile penetrating an aluminium plate. At the tip of the projectile large stresses are created which overcome the aluminium shear strength. It is the shear strength, a mechanical property of the aluminium plate that resists the penetration of the projectile and reduces projectile velocity.

![Figure 2-8: Penetration of a steel projectile on aluminium plate [22]](image)

Figure 2-9 represents the penetration mechanism of a spherical ram into an aluminium plate. Due to the penetration, fracture initiation is observed on the surface opposite to the impact where the critical stress exceeds, and a large amount of hoop stress is generated along the axis of symmetry.
2.6 Impact on brittle materials

Most brittle materials like SiC ceramics contain inhomogeneities such as small cracks or phase irregularities, which have different strengths from those of the actual matrix [63]. When these brittle materials are subjected to a large confining stress, these inhomogeneities can act as nuclei for new cracks to propagate and these micro cracks eventually coalesce to cause axial splitting [63]. The large amount of failure observed when a brittle material is subject to dynamic loading conditions is tensile in nature [63]. Hoop stresses induced by the radial movement of the material due to penetration are sufficient to nucleate tensile flaws which eventually coalesce and cause failure. Tensile spall planes are also generated by tensile waves reflected off free surfaces which are then able to interact with inhomogeneities and so nucleate flaws [63].

The effect of modifying and improving processing techniques can result in reduced grain-size microstructures within SiC ceramics and can produce improved mechanical properties [64]. The ballistic performance of the SiC is highly dependent on its microstructure. Microscopic analysis indicates that a decrease in grain size from 5—6 µm at 2200°C to 2—3 µm at 2000°C can increase the hardness value. It is important to improve the composition of sintering additives in order to minimise or eliminate defects, inhomogeneities, and density gradients within ceramics [65]. Krell et al. [66] displayed the
relationship between increased hardness and reduced grain size. The effect of modifying grain boundary behaviour can result in different mechanical behaviour within SiC ceramics [67].

Ceramic characteristics such as hardness and Young’s modulus increase with decrease in silicon content; however, the fracture toughness falls [68]. Fracture toughness is a vital parameter for the material properties and is generally described as the ability of a material that a pre-existing crack to resist fracture. Fractography analysis shows the relationship between the fracture mode and fracture toughness for lower silicon content, resulting in a smoother fracture surface. Different sizes and thicknesses of square SiC tiles were studied to evaluate the depth of penetration (DoP) [69]. It was concluded that if the core was deformed during ballistic impact, the DoP reduced with increase in tile size. The ballistic performance of the ceramic is also dependent on the distance from the point of impact to the tile edge, as the stress wave propagates within the ceramic until it interacts with the boundaries. The elastic impedance and elastic wave velocity can be found from the relationships given in Equation 2-6 and Equation 2-7 respectively. The importance of the impedance for defeating a projectile [38]. Moreover, the deformation of the core at the strike face and its penetration mechanism are vital to assessing the ballistic performance of the material used in different armours (discussed further in Chapter 4).

The elastic wave velocity can be calculated using the relationship in Equation 2-6

\[ Z = \frac{E}{\rho} \quad \text{Equation 2-6} \]

The elastic wave velocity can be calculated using the relationship in Equation 2-7

\[ c_\phi = \frac{E}{\rho} \quad \text{Equation 2-7} \]

where,

E = Young’s modulus

\[ \rho = \text{density} \]
2.7 Interdependence between hard and soft armours

During the ballistic impact, a compressive stress wave is initiated in both the strike face (ceramic) and the projectile during their interaction. The compressive wave is comprised of two components i.e. an elastic and an inelastic portion. The elastic portion moves at a faster speed as compared to the inelastic portion.

During its contact with the projectile, the ceramic causes deformation of the core and the formation of a shock wave. The duration of the shock wave is of utmost importance in comparison with the intact ceramic before it deforms. The compressive wave formed in the ceramic travels within the material until it reaches the tile boundaries where it gets reflected back as a damaging tensile stress wave. Due to the relatively low mechanical impedance of the resin layer, during the projectile interaction with the ceramic and the backing laminate, the compressive wave is reflected as a tensile wave that results in compression and causes damage. The radial wave expands away from the point of impact and is reflected as a tensile wave. Since the damage is localised only to the point of impact the surrounding intact material provides a region of confinement.

The interaction mechanism between the projectile and target also depends on the material and geometry of the projectile and the type of backing material (i.e. textile layers, laminated or not, present in the soft vest) and its support. Rosenberg et al. [70] demonstrated that the backing material thickness and its properties influence the final ballistic results. Backing materials having high stiffness and hardness provide improved ballistic efficiency as they provide backing support to the ceramic tile against failure under bending. The ballistic efficiency as described in Equation 2-8, is one of the measures for the ceramic performance to reduce the effectiveness of the projectile impact by eroding or deforming. It causes reductions in projectile mass and velocity, and is also dependent on ceramic properties. Woodward et al. [71] showed the influence of test conditions on the numerical values that determined the ballistic efficiency of a given target. The ballistic efficiency $\eta$ can be defined in Equation 2-8 [71]:

$$
\eta = \frac{\rho_B \Delta h_B}{\rho_c h_c}
$$

Equation 2-8

where,
\( \rho_B \) and \( \rho_c \) are the densities of the backing material and ceramic

\( \Delta h_B \) is the reduction in thickness of the backing material impacted by the ceramic

\( h_c \) is the thickness of the ceramic material

Work done by Reijer [3] assumed that the ceramic break-up time \( t_{\text{conoid}} \) is dependent on the time required for the radial fracture front to follow the reflected compressive wave to the ceramic, and this can be calculated by Equation 2-9 [3]:

\[
t_{\text{conoid}} = \frac{h_c}{\mu_{\text{ceramic}}} + \frac{h_c}{v_{\text{cracks}}} \quad \text{Equation 2-9}
\]

where,

\( h_c \) = thickness of ceramic

\( \mu_{\text{ceramic}} \) = velocity of elastic compressive wave

\( v_{\text{cracks}} \) = speed of radial crack front

### 2.8 Role of resin in armour

Resin is an important constituent of a composite armour system. The resin used for bonding ceramics can have significant implications on armour behaviour [72]. The influence of the mechanical impedance provided by resins on armour behaviour [73]. The residual velocity of the projectile after penetration can be dependent on the type of resin used in bonding the backing material [74]. Several researchers in the past indicated that the ceramic was the most important parameter in the target design, as it erodes the projectile [72-74]. It may be assumed that better and more efficient target designs can be achieved with thin layers of resin. The thin resin layer delays the ceramic damage and causes more erosion to the projectile. When the layer of resin is thicker, the failure of the ceramic occurs at an earlier stage, as the ceramic remains unsupported, and this is mainly caused by the bending mechanism [72].

During the ballistic impact, the resin causes a mismatch in acoustic impedance. High impedance can result in an increase in the energy transmission wave and
also can cause a decrease in the energy reflection wave, resulting in minimal ceramic distortion. Gao et al. [19] concluded that the addition of toughening particles increased the resin strength and improved the ballistic performance of the ceramic to fracture. The study conducted showed an increase in fracture failure was observed with a decrease in the strength of the resin.

Zera et al. [72] proposed a relationship to determine the time \( t_1 \) needed for a shock wave to attenuate, which is dependent on the velocity of the projectile \( (v_s) \), the velocity of the shock wave of the projectile material \( (U_p^s) \) and the diameter of the projectile \( (R_p) \), as in Equation 2-10

\[
t_1 = \frac{1.43 R_p}{U_p^s v_s}
\]

Equation 2-10

Numerical simulations showed that the fragmentation of the ceramic material occurs due to the tensile stress formed at the rear of the tile, followed by the propagation of cracks [72]. The rate of this failure is dependent on the thickness of the resin layer used.

Figure 2-10 and Figure 2-11 show the damage contours formed by using different types of polyurethane resin and epoxy resin with the thickness of resin layers being 0.5 mm and 1.5 mm. The damage to the ceramic is increased if the thickness of the resin layer is greater. As mentioned earlier, with a thicker layer of resin, the ceramic tile is less supported and the fragmenting failure of the tile is generally observed, due to bending. Moreover, the type of the resin used also has a paramount influence on the fragmentation of the ceramic. A thin resin layer provides better contact between the ceramic tile and the backing material.
The ceramic fragments get dispersed radially, during penetration from the projectile path, causing shear strain that leads to fracture in the material. The relationship between the strain rate and the resin thickness can be expressed by Equation 2-11, [75]:

$$\gamma_{rz} = \frac{v_c - v_b}{h_a}$$  \hspace{1cm} \text{Equation 2-11}$$

where,

$v_c$ and $v_b$ = radial velocities of ceramic and backing plate respectively in contact with resin
$h_a$ = thickness of resin layer
The initial event during the impact condition is vital as conical cracks are generated. The fragmentation of the rear face of the tile occurs as the elastic compression wave travels though the thickness. When this elastic wave reaches the ceramic/resin interface, bending in the tile causes circumferential stress and radial cracks propagate backward, as shown in Figure 2-12.

Zera et al. [72] concluded that armour system efficiency is dependent on resin thickness, ceramic spalling and energy absorption mechanisms.

### 2.9 Backing material thickness

Ceramic composite armours consist of a strike face ceramic bonded to a backing material. The backing material can be thin or thick. A thin backing material absorbs momentum from the projectile (which has penetrated the ceramic strike face) and its failure is observed by bending, [25]. A thick backing material results in little bending as compared to thin material, and perforation failure is usually observed due to residual projectile velocity [25]. Figure 2-13 and Figure 2-14 represent schematics for the sequence of events during a ballistic impact on confined (in the longitudinal direction of the path of the projectile) and unconfined armour respectively. In the confined armour case, the tile was bonded to a 38 mm thick aluminium backing and the impact side was confined by a 6.35 mm aluminium plate. For the un-confined armour, tile was bonded to a 6.35 mm aluminium backing plate and 150 mm spacing was provided for the backing to deflect or bend, followed by 38 mm aluminium plates.

As seen from Figure 2-13, the projectile impacting the ceramic, becomes eroded. Ejection of ceramic debris from the crater then occurs at high velocity in the opposite direction to that of the projectile. The compressive wave within the tile
propagates away from the impact site, causing a massive hydrostatic pressure increase in the tile, resulting in the crushing of the ceramic structure. Due to this, the confining plate is moved by the relief wave initiated, causing ceramic fracture. For the case where no confining plate is present, in front of the ceramic, the relief wave propagates through the ceramic, resulting in ceramic fracture and ceramic debris being ejected, as shown in Figure 2-14.

![Figure 2-13: Schematic of confined target with thick backing [25]](image1)

![Figure 2-14: Schematic of target with thin backing [25]](image2)

The confining effect on the ballistic failure mechanisms was examined by Sherman [76]. Two types of damage mechanism were identified – firstly, quasi-static damage (radial tensile cracks) is caused due to the bending mechanism of the back of the tile. Secondly, dynamic damage (spall cracks) are due to reflected and interacting stress waves [76].

2.10 Composite laminates made from textile materials

Composites are designed and manufactured to achieve unique properties and better performance characteristics. The use of high-strength, high-stiffness and lightweight materials has increased the credibility of composites for use in various applications, especially in armour. During impact loading conditions,
energy is transferred between the projectile and the backing material and may result in different failure mechanisms, energy dissipation and damage propagation due to projectile velocity variability during penetration [77].

Ballistic tests were conducted using a 7.62 mm AP round on composite materials [78]. They speculated that the composite layer acted to delay the fracture and fragmentation onset within the ceramic material, but the mechanism was not clear. They also mentioned that composite layers may provide lateral constraints on the ceramics, causing a delay in the spread of crack propagation and ceramic fragmentation. The research also emphasised that polymeric matrix composites (PMC) layers caused acoustic damping that affected stress-wave propagation, resulting in delayed fracturing. However, more tests need to be undertaken to clarify these results.

When the projectile impacts the composite, the primary yarns in direct contact with the projectile take the direct force and ultimately fail when the strain exceeds their maximum strain limit, as shown in Figure 2-15. The cone formation on the back of the laminate during ballistic testing was studied [79, 80]. This cone formation is due to transverse wave propagation that travels in the direction of the projectile. During penetration, the principal yarns in direct contact with the face of the projectile resist the penetration and the strain is higher in these yarns as compared to that of secondary yarns, as shown in Figure 2-15. The strain is highest at the point of impact and it reduces along the length of the fiber. The secondary yarns deform and absorb the energy, but experience different strain rates depending on their position, and a yarn pull-out failure is observed. The yarns that are adjacent to the point of impact experience a strain equal to the strain developed in the outermost layer of principal yarns. However, the secondary yarns that are furthest away from the point of impact experience less strain. The energy absorbed by secondary yarns is larger when compared to primary yarns due to the large surface area of secondary yarns compared with that of primary yarns, as illustrated in Figure 2-15. Figure 2-16 presents the transverse impact on a single-ply, fabric [85]. A series of research studies have been conducted on the effect and influence of crossover yarns [81-83]. It was observed that the transmission of longitudinal waves at cross-over yarns does not affect the strain wave away from the point of impact. Roylance [81] confirmed
that the strain wave generated within the fabric is not similar to that of single-fiber impact. It was found that transverse yarn interactions can have significant influence on ballistic results [82].

![Figure 2-15: Ballistic impact on composite target [77]](image)

![Figure 2-16: Impact on single ply fabric [84]](image)

### 2.10.1 Fabric structure/weave

Different types of weave structure e.g. plain weave, twill weave, basket weave, and satin weave may be used for backing composites. Weave types can be classified in terms of the warp and weft directions. The weave pattern within a
fabric structure determines the drapability and isotropy of strength. Woven ballistic fabrics are developed to achieve higher impact resistance to penetration with low cost. However, the crimp in woven yarns may lead to low energy failures. It was observed by Chitrangad [85] that this crimp has significant influence on the ballistic performance of the system. Crimp for plain-weave structure may be unbalanced i.e. warp yarns may be more crimped than weft yarns [85]. This is because weft yarns will break earlier than warp yarns as they need more time to elongate and decrimp. The study also investigated the density of the weave and, for the fabric to be used for ballistic application; it should possess a density range from 0.6 to 0.95. Generally, the response from the material properties of fabrics cannot be determined from the fibers alone, as studied by Roylance et al. [86]. However, the material properties and the geometry of the fabric are combined together to produce the structural response from the ballistic event. Cuniff [87] observed that loosely woven fabrics caused inferior ballistic performance. When a projectile is impacted on loosely woven fabric, it deflects transversely, causing yarn enlargement.

### 2.11 Fiber reinforced laminates

Fiber reinforced laminates are now often used to provide better armour systems. Laminates are flexible in terms of their construction and can be designed specifically for threat type to have improved structural characteristics. The disadvantages of laminates relate to increased cost and fabrication issues. Aramid-reinforced laminates possess one of the best protection-to-weight ratios for ballistic applications, [88].

Energy absorption characteristics of body armour systems under ballistic impact depend on material properties like material failure criteria, constitutive properties, fabric type, fabric weave, fabric ply numbers etc. The fundamental mechanics of ballistic impact was studied by several researchers [89-91]. These studies emphasised the detailed deflection mechanisms of several kinds of fabrics under ballistic impact. These studies incorporated the energy distribution mechanisms within fabrics under impact conditions and also the wave velocities
for various fabric types. The rate-dependent polymer response under ballistic loading that incorporates single-yarn response [92-95].

Crouch [96] concluded that in some cases resinly bonded, aluminium laminates showed greater energy absorption than conventional ballistic materials. Ballistic impact behavior of woven fabric such as E-glass/epoxy composites was studied by Naik et al. [77] to understand the energy absorption and damage mechanism. He concluded that the major energy-absorbing mechanisms are the deformation of the secondary yarns and the tensile failure of the primary yarns. In another study, a glass fiber epoxy composite was subjected to ballistic testing [88]. He concluded that 30 plies of glass fiber-epoxy were required to obtain bulletproof laminates.

2.12 Longitudinal and transverse wave fronts

The high strength of single-fiber does not necessarily guarantee a superior soft armour vest. The understanding of textile structure ballistics must be preceded by an understanding of the single-fiber response [97]. Single-fiber tests are often used as screening tests for ballistic protection materials.

In general, wave propagation phenomena within fibers are considerably less complicated than within weaves or composites, as the possibility of unrestrained transverse contraction within fibers is eliminated [97]. When the projectile hits the fiber, two types of wave front are generated at the point of impact (longitudinal waves and transverse waves) as illustrated in Figure 2-17. The longitudinal wave front travels along the length of the fiber axis and the transverse wave front travels along the direction of the projectile. Behind the longitudinal wave front, the material flows in towards the impact point with a constant velocity and strain [86]. The transverse wave propagates slowly as compared to the final longitudinal wave. During the transverse wave front propagation, the material-inward flow velocity ceases abruptly and is replaced by transverse particle velocity. This particle velocity is the same as that of the projectile velocity. Behind the transverse wave front, all particle velocities are equal in magnitude and direction to the projectile velocity [86].
The ballistic testing of composite multi-layered plies for ballistic material was studied in detail [83, 98-100]. A series of experimental tests conducted on ballistic materials with multi-ply systems have been analysed using impact conditions [87, 101]. Theoretical analysis conducted by Cunniff [87] found that the energy absorption mechanism of the spaced single plies is more than the layered system. Lim et al. [101] found that the energy absorption mechanism of the layered system was higher than the spaced single plies when impacted using different projectile geometry. The failure mechanism within the multi-layered composite is dependent on various parameters like – impacting velocity, shape of the projectile, fiber-resin matrix properties, etc. For ballistic applications, composites with multi-layered plies are required to have weak adhesion bonding. During the composite penetration, layers adjacent to the initial point of impact behave in elastically and the ones at the rear behave elastically. It was also noted that the failure mode observed during penetration was due to shearing failure, forming a plug. Work done by Lee [98] on failure observed on Spectra® fibers is shown in Figure 2-18. Once a plug was formed, delamination was observed, causing a fiber pull-out failure and tensile failure at the rear of the laminate. Iremonger [99] showed the shear failure mechanism due to the sharp edges of the projectile. Scott [100] stated that during the penetration failure, in the first few layers fiber stretching was evident, as can be seen from Figure 2-18(b).
In this current research, each RSSC ceramic tile is clad on both the front and rear face using a woven Kevlar® aramid (300 gsm) with 4 yarns up and 1 yarn down (twill weave) and commercial-grade epoxy resin. This epoxy resin is also used to hold the backing laminate to the clad RSSC tile, on both the front face and the rear face (refer to Chapter 4—6). The reason for cladding the RSSC is to reduce frontal spall, which has little impact on ballistic performance other than to hold the radial and circumferential cracks together in case of multi-hit impacts, as illustrated by Woodward et al. [25]. The woven Kevlar® aramid is usually resin-impregnated to prevent any lateral movement of the yarn during its interaction with the projectile in order to increase the amount of energy absorbed within the aramid as mentioned by Lee et al. [83]. The details of the various armour styles manufactured for the current research work are discussed more in detail in Chapter 4—6.
3 Mechanical testing

3.1 Introduction

In this study, the Kevlar® used for clad application and Kevlar® XP™ used in layers for the backing laminate and soft vests (more details can be obtained in Chapter 4) behind the ceramic strike face were subjected to a series of mechanical (tensile) tests. The Kevlar®, Kevlar® XP™ and RSSC were also analysed under SEM (scanning electron microscopy) examination to understand their structure. Lastly, the RSSC strips were subjected to bend tests to compare the bending rigidity for different thicknesses. The bend tests on RSSC strips were also compared introducing a coating of resin, Kevlar® aramid layer and layer of Kevlar® aramid under tension application.

Note: Due to propriety naute of this research work, some of the information has intentionally not been included in some significant sections (e.g. armour styles mass per unit area, fabrication technique etc.).

3.2 Kevlar®

A loose, twill weave structure, woven 300 gsm Kevlar® aramid was used for the cladding application. Figure 3-1 represents the Kevlar® aramid used for cladding application.

Note: the warp direction is referred as the lengthwise yarns on a loom. The weft direction is referred as the horizontal yarns that are interlaced with warp direction.
3.3 Reaction-Sintered Silicon Carbide (RSSC)

Figure 3-2 shows the composition of the different materials present in the RSSC tiles that were used for scanning electron microscopy (SEM) analysis. The surface topography for the RSSC was not uniformly distributed and the Si crystals particles were scattered unevenly over its face. The RSSC tiles received from the manufacturer and used for this research work were not completely flat; the limitation in flatness of the RSSC tiles is due to the vertical fabrication technique used to manufacture them in bulk quantities. The surface of the RSSC tiles used as received from the manufacturer was also uneven and had grinding marks on them, as shown in Figure 3-3 to Figure 3-5. However, one could physically feel the different grain sizes and structure on the surface of RSSC and classify them as coarse, smooth and fine, as shown in Figure 3-3 and Figure 3-4. Figure 3-5 represents the SEM analysis for the polished surface of the RSSC. The polishing was carried out through an external source and one can clearly observe the vital difference observed between Figure 3-3 and Figure 3-5. Figure 3-5 shows the different sizes of the crystals, grain structures and grain boundaries that were enhanced during polishing.
Figure 3-2: Si crystals observed on the RSSC surface

Figure 3-3 Different crystal structures on RSSC surface

Figure 3-4: Grinding marks on RSSC (100µm resolution)
3.4 Kevlar® XP™

Figure 3-6 presents the Kevlar® XP™ used in layers for the backing material behind the ceramic strike face, which were subjected to a series of mechanical (tensile) tests with different orientations to assess its structure. As mentioned in Chapter 1, a single layer of Kevlar® XP™ was constructed by abutting flat tapes of parallel Kevlar® filaments to form one side of the fabric, with a bonding layer in between. A second layer of Kevlar® was similarly bonded on the other side, oriented at 90° to the first. Figure 3-6 represent a single layer of Kevlar® XP™ ply and the arrow shows the direction of filaments on the front face. The lines of stitching 5mm apart across the surface of the aramid were not made up of Kevlar®. The stitching served only to hold the yarns together during the fabrication of the fabric.
3.5 Orientation of Kevlar® XP™ for tensile testing

Due to the fabric structure, Kevlar® XP™ was cut into different orientations, as shown in Figure 3-7 and Figure 3-8. During mechanical testing, the tensile force acting on the Kevlar® XP™ fabric was perpendicular to the stitching direction as shown in Figure 3-7. However, the tensile force acting on the Kevlar® XP™ fabric was parallel to the direction of stitching, as shown in Figure 3-8 shows the specimen cut parallel to the fiber length on the front face of the Kevlar® XP™ where the stitching direction is inclined at 45°. It can be clearly seen from Figure 3-8 that only this orientation type has the filaments fully bridging the gauge length, as compared to the specimens shown in Figure 3-7.
Figure 3-7: Perpendicular and parallel stitching directions

Figure 3-8: Stitching direction inclined at 45°
3.5.1 Mechanical testing on Kevlar® XP™

The mechanical testing of the Kevlar® XP™ aramid was conducted at RMIT’s Materials Testing Laboratory, using an 810 MTS, 50kN load cell machine, as shown in Figure 3-9. The tensile testing was conducted on specimens that were cut in the orientations as shown in Figure 3-7 to Figure 3-8 respectively. In Figure 3-7, none of the filaments fully bridge the gauge length, so these specimens actually test the performance of the stitching and degree of bonding of the opposite faces of the Kevlar® XP™ fabric.

![Figure 3-9: MTS testing machine](image)

3.5.2 Specimen preparation

The Kevlar® XP™ fabric was cut into strips of 25 mm wide and 200 mm in length. The gauge length of the specimens was kept constant at 100 mm with an increment of 10 mm/min. The jaws used for conducting tensile testing were able to prevent slippage of the Kevlar® XP™ fabric with the help of inserts between the jaws to prevent the aramid slipping. Examples of these specimens are illustrated in Figure 3-10 and Figure 3-11.
3.6 Tensile test results

3.6.1 Tensile test for Kevlar®

The tensile testing for the woven Kevlar® aramid was conducted at RMIT University. The woven aramid had a loose twill weave structure with 4 yarns up and 1 yarn down. The twill-weave structure is also classified as a diagonal weave and it possesses superior wet-out and drape properties over the plain weave. The pick and end density of the woven Kevlar® was approximately 16 (ends/cm) and 14.5 (picks/cm).

The woven Kevlar® was cut into small sections of 25 mm in width and 200 mm in length as shown in Figure 3-12. In the specimen, with the width of 25 mm
there were 14 yarns (approx.) present. The gauge length during the tensile testing of the woven Kevlar® was kept at 100 mm and the increment during the testing was also maintained at 10 mm/min. Since the woven Kevlar® had a loose structure, it was resin-impregnated at both the ends (prior to being held between the jaws) to hold the woven Kevlar® and prevent any inter-yarn slippage, as shown in Figure 3-12. The tensile testing (5 samples) was carried out in order to determine the force applied on the rear face of the RSSC cladding (refer to Chapter 6 for more information).

Figure 3-12: Woven Kevlar® (300gsm) 4/1 twill weave (before test)

Figure 3-13 represents the specimens after the tensile tests. It is clearly evident that yarn fibrillation and yarn failure where observed during the testing. The maximum load that was achieved prior to yarn failure was observed at approximately 4 kN. Prior to yarn failure, uncrimping of the yarns was attained in the warp direction i.e. parallel to the force of applied tension.
3.6.2 Tensile test perpendicular to stitching direction

During the tensile testing, where the stitching of Kevlar® XP™ fabric was perpendicular to the tension direction, the failure was observed near the jaws holding the aramid. It was due to the tensile force that acts on the specimen i.e. yarns within the gauge length distance get skewed, causing failure in the stitching. The stitching failure causing twisting of yarn that resulted in yarn failure and fibrillation was observed when further tensile load was applied. The failure also results in debonding between the front and rear yarn faces of the Kevlar® XP™. This failure is predominantly observed near the jaw surface, as illustrated in Figure 3-14.
3.6.3 Tensile test parallel to stitching direction

During the tensile testing, twisting and necking was also observed within the Kevlar® XP™ fabric, as shown in Figure 3-15. However, the initial failure was observed in the stitching thread, which provided a greater contribution to the tensile performance than when the load was applied perpendicular to the stitching. Once the stitching failure was observed, the load was taken only by the filaments at 45° causing those to twist near the top and bottom jaws. Debonding was observed between the front and rear faces of the Kevlar® XP™ fabric but was mostly observed near the top jaw. Lastly yarn fibrillation was observed near the top and bottom jaws.

![Figure 3-15: Stitching failure observed in Kevlar® XP™ fabric (y-axis)](image)

Table 3-1 presents the average tensile results (5 samples) for the single layer of the Kevlar® XP™ fabric cut in different orientations with respect to the testing. It is clearly evident that the tensile strength of the Kevlar® XP™ fabric is greater when the tensile force is applied parallel to the stitching direction, as shown in Figure 3-15, rather than perpendicular to the stitching direction, as shown in Figure 3-14, for the single layer. The difference in results between specimen-1A and specimen-8 is due to the fact that the filaments in the specimens do not bridge the gauge length, as shown in Figure 3-7 and Figure 3-8. Specimen-12 shows the maximum average load capacity of 4094 (N) as compared to specimen-1A with 650 (N) and specimen-8 with 738 (N). Specimen-12 shows
the true characteristics of this aramid, as it was cut parallel to the full length of the fiber for one face of the fabric to take the load, as shown in Figure 3-8.

### 3.7 Optical microscopy

Microscopic analysis of failure mechanism was performed under an optical microscope. Stitching failure, as mentioned above, can be clearly observed in Figure 3-16. The debonding between the front and rear surfaces of the Kevlar® XP™ fabric is clearly evident.

![Figure 3-16: Stitching and debonding failure observed in Kevlar® XP™ fabric](image)

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Direction of stitching</th>
<th>Number of Kevlar® XP™ layers</th>
<th>Average maximum load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen-1A</td>
<td>x direction</td>
<td>1</td>
<td>650</td>
</tr>
<tr>
<td>Specimen-8</td>
<td>y direction</td>
<td>1</td>
<td>738</td>
</tr>
<tr>
<td>Specimen-12</td>
<td>Diagonal</td>
<td>1</td>
<td>4094</td>
</tr>
</tbody>
</table>
mentioned in Chapter 2, when the projectile strikes a fiber, two waves propagate i.e. longitudinal and transverse waves, from the point of impact, as shown in Figure 3-17. The presence of glue or a bonding layer between the adjacent faces of Kevlar® XPTM or any asymmetry introduced by the stitching will affect the wave propagation and the energy absorbing mechanism.

![Figure 3-17: Ballistic fiber impacted by projectile [7]](image)

*Note: however, while conducting the ballistic testing for this research work, the stitching direction of the Kevlar® XPTM fabric backing material was along the y-axis. The details of the ballistic testing will be discussed in depth in Chapter 4.*

## 3.8 Scanning Electron Microscopy (SEM) analysis

SEM analysis for Kevlar® and Kevlar® XPTM fabric was conducted at RMIT’s Microscopy and Microanalysis Facility (RMMF). The SEM was conducted using a Philips XL30 SEM machine. The main purpose of SEM was to identify and understand the Kevlar® and Kevlar® XPTM fabric structure. The specimens were coated with a thin layer of gold to be conductive for SEM analysis. The mounted specimen was analyzed at different magnifications under a complete vacuum condition. Figure 3-18 represents the SEM image for the woven Kevlar® aramid used for clad application (more details can be obtained from Chapter 4). Figure 3-19 represents the lubricating gel that was observed at the point where the stitching and Kevlar® XPTM filaments overlapped. It is assumed that this gel was applied during stitching of the Kevlar® XPTM filaments to amid manufacture. Due to the proprietary nature of the aramid, it was not possible to retrieve more information about this product. The diameter of the Kevlar® XPTM filament was measured to about 10µm as seen in Figure 3-20. Figure 3-21
represent the front and rear face of the Kevlar® XP™ filaments, illustrating the cross-over of the yarns.

Figure 3-18: SEM image of Kevlar® aramid

Figure 3-19: SEM image of Kevlar® XP™
Three-point and four-point bend tests were conducted on RSSC tiles and RSSC strips to determine critical insight into maximum bending load and maximum bending stresses. The interlaminar shear strength is a critical parameter in composites due to its relatively low value compared with the longitudinal tensile strength. In this research, three-point and four-point bending tests have been carried out for comparison to measure the interlaminar shear strength of RSSC tiles and RSSC strips of different thicknesses with epoxy resin.
3.9.1 Three-point bend test

Figure 3-22 to Figure 3-24 represents the flexure test for 150 mm x 150 mm RSSC tiles. The tiles were coated with a thin layer of commercial-grade epoxy resin. A similar amount of epoxy resin was coated on the front and rear faces for three different thicknesses of RSSC tiles (4 mm, 6.5 mm and 8 mm), as shown in Table 3-2. The resin-coated RSSC tiles were cured by heating in an oven at 80°C for 1 hour.

Table 3-2 represents the results for maximum bending load (kN) and maximum bending stress (MPa) for each tile thickness. The results were compared with a single tile 8 mm-NR i.e. no resin, which was also subjected to a three-point bend test but with no epoxy coating. It is clearly evident that the addition of a thin layer of epoxy resin coating on the 8 mm RSSC tile improves the maximum load from 3.06 kN to 7.38 kN, as shown in Figure 3-25. The maximum bending stress for 8 mm RSSC tiles with and without resin varied from 23.87 MPa to 55.91 MPa as shown in Figure 3-26. The addition of resin coating helps to delay crack initiation and prevent crack propagation within the RSSC. It is also seen clearly that cracks formed during tests; as shown in Figure 3-22 to Figure 3-24 the cracks did not follow the line of the fulcrum due to the bend in the tiles. For brittle materials such as ceramics, these show a linear relationship of load and deflection under the elastic limit, where yielding occurs on a thin layer of the specimen surface at the midspan. This in turn leads to crack initiation, which finally proceeds to specimen failure.

*Note: as mentioned earlier since the RSSC tiles were not completely flat, the crack initiation for each 4 mm, 6.5 mm and 8 mm thickness was likely to be different.*
Table 3-2: Maximum bending load and bending stress comparison vs. tile thickness

<table>
<thead>
<tr>
<th>RSSC tile thickness (mm)</th>
<th>RSSC tile thickness after resin coating (mm)</th>
<th>Maximum load (kN)</th>
<th>Maximum bending stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.4</td>
<td>2.15</td>
<td>55.51</td>
</tr>
<tr>
<td>6.5</td>
<td>6.83</td>
<td>5.18</td>
<td>55.59</td>
</tr>
<tr>
<td>8</td>
<td>8.35</td>
<td>7.38</td>
<td>55.91</td>
</tr>
<tr>
<td>8-NR*</td>
<td>NA</td>
<td>3.06</td>
<td>23.87</td>
</tr>
</tbody>
</table>

NR – no resin

Figure 3-22: 4 mm resin-coated RSSC showing major crack structures

Figure 3-23: 6.5 mm resin-coated RSSC showing major crack structures
Figure 3-24: 8 mm resin-coated RSSC showing major crack structures

Figure 3-25: Maximum bending load vs. Tile thickness

Figure 3-26: Maximum bending stress vs. Tile thickness
3.9.2 Four-point bend test

Since the RSSC tiles were not completely flat, they were cut into 30mm wide and 150 mm length strips to better test true bending. The tiles were cut using a water-jet cutter. Figure 3-27 and Figure 3-28 represents the four-point bend layout for the RSSC strips. The crack initialisation was observed on the top half of the RSSC strip, as shown in Figure 3-28. The maximum bending load for 4 mm was 0.91 kN; 1.63 kN for 6.5 mm, and 3.20 kN for 8 mm respectively as shown in Figure 3-29. However, the bending maximum bending stress for 4 mm is 62.42 MPa, 6.5 mm is 41.49 MPa and 8 mm is 53.63 MPa, as shown in Figure 3-30. The variation in the results achieved from complete RSSC tile to RSSC strips is attributed to the flatness in the tile.

In general for brittle materials such as ceramics, they do not have a yield point and so the rupture strength and the ultimate strength are the same. Within the elastic range, brittle materials show a linear relationship of load and deflection; however, where yielding occurs, it leads to crack initiation, which finally proceeds to specimen failure.

Figure 3-27: Four-point bend test
Figure 3-28: Resin-coated RSSC strips for four-point bend tests

Figure 3-29: Maximum bending load vs. tile thickness

Figure 3-30: Maximum bending stress vs. tile thickness
3.9.3 Four-point bend test (RSSC strips)

In total five sets of 4 mm RSSC and two sets of 6.5 mm RSSC tiles were cut into smaller sections to conduct four-point bend tests as shown in Figure 3-31. The five sets of 4 mm RSSC tiles were reduced from 6.5 mm thickness tiles and it could be observed that one side of the 4 mm RSSC tiles was ground compared to the other side, which had a raw surface. Due to this grounding of the tiles, the 4 mm RSSC tiles had variation in thickness across the length of the strip from 4.6 mm – 4.8 mm. However, for the 6.5 mm RSSC strips, both the surfaces were raw surfaces and the bend tests for both 4 mm and 6.5 mm was conducted on the raw surfaces with different combinations as illustrated in Tables 3-3 and 3-4.

Figure 3-31: 4 mm and 6.5 mm RSSC strips

Figure 3-32: Epoxy resin-coated (6.5 mm) and woven Kevlar® coated (4 mm) RSSC strips
The 4 mm RSSC strips were categorized under different combinations i.e. dry RSSC (no epoxy resin coating), epoxy resin-coated (one side only), epoxy-resin and aramid-coated (one side only), epoxy-resin and aramid-coated in tension (one side only) and epoxy resin and aramid coated in different orientations (D/O) (one side only).

Note: the term D/O specifies different orientation of the woven Kevlar® resin-coated adjacent to the RSSC strips. In Table 3-3, sample 3 and sample 4 are similar; however, the orientation of the woven Kevlar® adjacent to the RSSC strips is varied due to the weave structure of the woven Kevlar® as shown in Figure 3-34.
The 6.5 mm RSSC strips were epoxy resin-coated (one side only) and epoxy resin and aramid coated in tension (one side only) as shown in Figure 3-32 and Figure 3-33. The layout for this testing is shown in Figure 3-35 and the distance between the loading noses and support span is constant across all the series of the tests.

Table 3-3 compares the maximum failure load and maximum flexure stress for both 4 mm RSSC strips. It can be said when the RSSC strips were coated with a thin layer of epoxy resin, the crack initiation failure mechanism was delayed, resulting in increasing the failure load and flexure stress from 860 N (sample -1) to 1150.2 N (sample-2) and 56.2 MPa to 66.3 MPa. When a layer of woven aramid i.e. Kevlar® aramid was added with a thin layer of epoxy resin the failure load increased further in the range of 1276.0 N (sample-3) to 1461.0 N (sample-4), depending on the orientation of the yarn adjacent to the RSSC strips. It shows that by varying the orientation of the Kevlar® aramid, we tend to get variation in the results obtained. However, in sample-5, when the Kevlar® aramid was put in tension, the failure load and flexure stress were reduced to 1183.3 N and 56.5 MPa as compared to sample-3.
<table>
<thead>
<tr>
<th>Samples</th>
<th>RSSC tile thickness (mm)</th>
<th>RSSC tile thickness after resin coating (mm)</th>
<th>Maximum failure load (N)</th>
<th>Maximum flexure stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample-1</td>
<td>4 mm dry RSSC</td>
<td>4.3</td>
<td>860.0</td>
<td>56.2</td>
</tr>
<tr>
<td>Sample-2</td>
<td>4 mm RSSC epoxy resin-coated (one side only)</td>
<td>4.6</td>
<td>1150.2</td>
<td>66.2</td>
</tr>
<tr>
<td>Sample-3</td>
<td>4 mm RSSC epoxy resin and aramid-coated (one side only)</td>
<td>5.1</td>
<td>1276.0</td>
<td>60.9</td>
</tr>
<tr>
<td>Sample-4</td>
<td>4 mm RSSC epoxy resin and aramid-coated in different orientations (D/O) (one side only)</td>
<td>5.0</td>
<td>1461.0</td>
<td>70.8</td>
</tr>
<tr>
<td>Sample-5</td>
<td>4 mm RSSC epoxy-resin and aramid-coated in tension (one side only)</td>
<td>5.1</td>
<td>1183.3</td>
<td>56.5</td>
</tr>
</tbody>
</table>

Figure 3-36 and Figure 3-37 presents the comparison of the 4 mm RSSC strips with different combinations. It can be said by adding a thin layer of epoxy resin layer and Kevlar® aramid we can see increase in failure load and flexure stress. This is due to delay in crack initiation procedure.
Table 3-4 presents the maximum failure load and maximum flexure stress for 6.5 mm RSSC strips. For 6.5 mm, a failure load of 2.5 kN was observed with strips coated with epoxy resin only, however, when the strips were coated with a thin layer of epoxy resin along with Kevlar® aramid in tension, the failure load dropped to 2.18 kN and a similar trend was observed for flexure stress as shown in Figure 3-38 and Figure 3-39. The tension applied on samples in case for both 4 mm and 6.5 mm RSSC strips, showed lower failure loads than its counterpart, however, the strain rate for these samples showed some increase causing delay in failure mode (more details in Chapter 7).
Table 3-4: 6.5 mm RSSC strips comparison

<table>
<thead>
<tr>
<th>Samples</th>
<th>RSSC tile thickness (mm)</th>
<th>RSSC tile thickness after resin coating (mm)</th>
<th>Maximum failure load (N)</th>
<th>Maximum flexure stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample-1</td>
<td>6.5mm RSSC epoxy-resin coated (one side only)</td>
<td>6.8</td>
<td>2557.1</td>
<td>69.7</td>
</tr>
<tr>
<td>Sample-2</td>
<td>6.5mm RSSC epoxy-resin and aramid-coated in tension (one side only)</td>
<td>7.2</td>
<td>2185.5</td>
<td>53.1</td>
</tr>
</tbody>
</table>

Figure 3-38: 6.5 mm RSSC strips failure load comparison

Figure 3-39: 6.5 mm RSSC strips failure load comparison
4 First ballistic test (trial #1)

4.1 Introduction

Three ballistic tests were undertaken to test various manufactured armour styles. In the first ballistic test (Trial#1), a range of armour styles was proposed and manufactured using the same batch of 4 mm RSSC plates as the initial strike face – clad with woven Kevlar® aramid on the front and rear faces (as shown in Figure 4-1, Figure 4-2 and Figure 4-3) and backed by various combinations of 16 layers of Kevlar® XPTM laminated or not with Linear Low Density Polyethylene (LLDPE). The foreshadowed ballistic tests were intended to set a benchmark against which future innovative developments in armour styles manufactured could be compared. Based on past experience and knowledge of current practice, a series of configurations was proposed by Australian Defence Apparel (ADA)\(^1\) for ballistic performance of these manufactured armour styles.

*Note: the first ballistic test, second ballistic test and third ballistic test are classified in this thesis as – Trial #1, Trial #2 and Trial #3 and they all have the similar areal density across the different sets of manufactured armour styles.*

4.2 Armour styles

The Trial-1 ballistic test consisted of five armour styles - Basic Armour (BA-1), Optimum Armours (OP-1 to OP-3) and Standalone Armour (SA-1), as shown in Table 4-1.

- **BA-1** armour style consisted of an RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was held in front of 16 layers of soft Kevlar® XPTM fabric (not bonded and including no LLDPE layers).

- **OP-1** armour style consisted of a cladded RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was bonded using epoxy resin to the front of a backing laminate manufactured from four layers of Kevlar® XPTM and three interleaved layers.

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\(^1\) Australian Defence Apparel Pty Ltd, 14 Gaffney Street, Coburg, VIC 3058, Australia
layers of LLDPE. Behind this backing laminate were 12 separate layers of soft Kevlar® XPTM fabric.

- OP-2 armour style consisted of a cladded RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was bonded using epoxy resin to the front of a backing laminate manufactured from eight layers of Kevlar® XPTM and seven interleaved layers of LLDPE. Behind this laminate were eight separate layers of soft Kevlar® XPTM fabric.

- OP-3 armour style consisted of a cladded RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was bonded using epoxy resin to the front of a backing laminate manufactured from 12 layers of Kevlar® XPTM and 11 interleaved layers of LLDPE. Behind this backing laminate were four separate layers of soft Kevlar® XPTM fabric.

- SA-1 armour style consisted of an RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was bonded using commercial-grade epoxy resin to the front of a fully backing laminate manufactured from 16 layers of Kevlar® XPTM fabric and 15 layer of LLDPE.

*Note: due to the proprietary and commercial-in-confidence nature of this research work, the name of the epoxy resin and the cladding technique used in manufacturing the armour styles cannot be disclosed.*

The schematic representation of each armour style is shown in Figure 4-1, Figure 4-2 and Figure 4-3. Each armour style was clad RSSC with Kevlar® aramid on the front face as well as rear face using an epoxy resin fabricated under heat and pressure. The front strike face of the RSSC tile (that first impacted by the projectile) was coated with a thin layer of epoxy resin, followed by a layer of woven Kevlar®. This Kevlar® cladding was itself later coated with a thin layer of epoxy resin such that it was totally encapsulated in the epoxy resin. This was a cladding technique used for almost all manufactured armour styles used in all three trials.
However, the rear face of the RSSC tile especially for BA-1 armour style, was comprised of an epoxy resin on the RSSC rear face followed by the woven Kevlar® aramid. There was no layer of epoxy resin present after the woven Kevlar® aramid (so this was a “dry” RSSC tile) and the clad RSSC tile was only held against the sixteen layers of the soft vest during the ballistic test by straps. In the case of the other armour styles OP-1, OP-2, OP-3 and SA-1, the cladding of the RSSC tile rear face was consistent throughout. It was coated with a thin layer of epoxy resin, which was clad with the woven Kevlar®. When the backing laminate was subsequently added, a second thin layer of epoxy resin was applied over the woven Kevlar® aramid and this glued the backing laminate to the back of the clad RSSC tile. The remaining layers of soft vest were held in place for the ballistic test, as with BA-1, by straps. It was only the SA-1 armour style in which there were no layers of soft vest. This amounted to the “wet” arrangement for the RSSC tile.
Table 4-1: Armour styles representation for ballistic tests

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Basic Armour (BA-1)</th>
<th>Optimum Armour (OP-1 &amp; OP-3)</th>
<th>Optimum Armour (OP-2)</th>
<th>Standalone Armour (SA-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile or bullet direction of impact</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike face</td>
<td>4 mm RSSC</td>
<td>4 mm RSSC</td>
<td>4 mm RSSC</td>
<td>4 mm RSSC</td>
</tr>
<tr>
<td>Backing laminate</td>
<td>NONE</td>
<td>4 or 12 plies of Kevlar® XPTM/ 3 or 11 plies of LLDPE</td>
<td>8 plies of Kevlar® XPTM/ 7 plies of LLDPE</td>
<td>16 plies of Kevlar® XPTM/ 15 plies of LLDPE</td>
</tr>
<tr>
<td>Soft vest</td>
<td>16 plies of Kevlar® XPTM</td>
<td>12 or 4 plies of Kevlar® XPTM</td>
<td>8 plies of Kevlar® XPTM</td>
<td>NONE</td>
</tr>
</tbody>
</table>

Figure 4-1: Schematic of BA-1 armour style
4.3 Manufacture of armour styles

The raw materials to manufacture and ballistic test the armour styles, i.e. Kevlar® aramid, Kevlar® XP™, RSSC tiles, epoxy resin and LLDPE, etc., were supplied by ADA. The fabrication of the backing laminate was conducted at the Defence Science and Technology Organisation (DSTO), Melbourne, Integrated Composites Facility by Advanced Composite Structures, Australia (ACS-A) and RMIT University facilities. The final assembly of the ballistic armour styles was later completed in-house by ADA and involved the following steps:

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2 DSTO Melbourne, 506 Lorimer Street, Fishermans Bend, VIC 3207, Australia
3 Advanced Composite Structures Australia Pty Ltd, 506 Lorimer Street, Fishermans Bend, VIC 3207, Australia
4 RMIT University, School of Fashion and Textiles, 25 Dawson Street, Brunswick, VIC 3056, Australia
• cladding a single layer of a woven Kevlar® aramid fabric onto the RSSC strike plate using an resin
• epoxy resin bonding the backing laminate onto the clad RSSC tile for armour style OP-1, OP-2, OP-3 and SA-1.

The constituents of the backing laminate (i.e. LLDPE and Kevlar® XP™) are shown in Figure 4-4 and Figure 4-5 with one of the final clad armour styles (OP-3) shown in Figure 4-6. The RSSC tiles used for the ballistic tests were purchased from the Modern Ceramics Company (MCC)\(^5\) as 150 mm × 150 mm × 4 mm tiles to an ADA proprietary specification. The general properties of the specific ADA-grade RSSC tiles used in these armour style composites is as follows

• nominal thickness = 4.0 mm
• bulk density = 3.06 ± 0.02 g/cm\(^3\) - refer foot note 5.

\(^5\) Modern Ceramics Company Pty Ltd (Military Ceramics Corp), 105 Carnarvon Street, Silverwater, NSW 2128, Australia
The composition of backing laminate and soft vests in relation to the armour styles manufactured along with the number of specimens manufactured for ballistic testing are shown in Table 4-2.

Table 4-2: Backing laminate and soft vest details

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Layers of Kevlar® XP™ in the soft vest</th>
<th>Number of Kevlar® XP™ layers</th>
<th>Number of alternating LLDPE layers</th>
<th>Number of replicates for ballistic testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Armour (BA-1)</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Optimum Armour (OP-1)</td>
<td>12</td>
<td>4</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Optimum Armour (OP-2)</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Optimum Armour (OP-3)</td>
<td>4</td>
<td>12</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Standalone Armour (SA-1)</td>
<td>0</td>
<td>16</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Total number of combinations manufactured 39
4.4 Backing laminate fabrication

Since large number of armour styles were required for ballistic tests, an in-house process was developed that could vacuum-bag/heat-cure multiple backing laminates in one cure cycle, thereby resulting in a significant reduction in manufacturing time and cost. The manufacturing technique used in fabricating backing laminate is given in next section 4.4.1.

4.4.1 Fabricating technique

Loose layers of Kevlar® XP™ fabric (as illustrated in Table 4-2) were laid on top of each other with the parallel lines of stitching orientated in the same direction. A single layer of LLDPE was inserted between each Kevlar XP™ layer such that, under heat and pressure, the LLDPE infiltrated into the Kevlar XP™ fabric to form a relatively stiff laminate. The schematic layout of the backing laminates and the temperature-control thermocouple is shown in Figure 4-7. As indicated, specimen-7 contained no LLDPE and was only used to monitor the internal temperature of the oven to ensure that the temperature of the fabrication process was accurately maintained. The thermocouple was placed inside the midsection of this backing laminate and later this specimen was discarded after curing.

Figure 4-7: Schematic layout of backing laminate assemblies on aluminium plate

The first manufacturing step was to cover the aluminium plate (900 mm x 600 mm) with a glass-fiber Teflon®-coated release film, on which the backing
laminate materials (Kevlar® XPTM/LLDPE) were laid, as shown in Figure 4-7, and with greater cross-sectional detail in Figure 4-8. The release films were used to isolate the laminate material from the aluminium plate and the caul plate and allow ease of stripping after curing. A layer of breather material was placed over the top of the caul plate to allow uniform vacuum to be applied over the backing laminate material (Kevlar® XPTM/LLDPE). The plastic vacuum bag was placed over the entire assembly and sealed with sealant tape that could withstand a temperature of 180°C.

*Note: caul plate is a metal plate used in the curing process during composite lay-up to reduce process time. The caul material is used to assist heat transfer from the press plate to the load in order to increase resin curing of the composite.*

The whole assembly containing the backing laminate material (Kevlar® XPTM/LLDPE) was placed inside the oven at room temperature. The oven was set to reach 140°C in increments of 5°C per minute at half vacuum (−50 kPa). After reaching 140°C, a full vacuum was applied (−100 kPa) and held for 90 minutes. The vacuum pressure was controlled by the technical staff using a control valve. Once this cycle was completed, the oven was switched off; however; the full vacuum of −100 kPa was maintained while the backing laminate material cooled down to room temperature.

![Figure 4-8: Cross sectional view for backing laminate fabrication](image)

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4.5 *Avtomat Kalashnikova 47 (AK-47)*

The *Avtomat Kalashnikova 47 (AK-47)* was the world’s first successful automatic/semi-automatic assault rifle, and one of the most widely used around the world. The projectile chosen for ballistic testing is that used for this rifle. It has a mild steel core, as shown in Figure 4-9 and Figure 4-10. Physical measurements of the steel core, copper jacket and lead filler were conducted and it was found that the weight of the steel core was ~3.58 g, the weight of the copper jacket was 2.12 g and the weight of the lead filler was 2.05 g respectively. The bullet has a calibre of 7.62 mm and a full cartridge length of 39 mm.

![Figure 4-9: AK-47 bullet components [2]](image)

![Figure 4-10: AK-47 bullet with its mild steel penetrator](image)

There are many factors that affect the complex penetration mechanism of each armour style manufactured, i.e. the type of projectile used, its geometry, velocity, the strike face, clad technique, material and local impacting conditions, etc. In the trial #1 of 39 ballistic tests, a range of velocities was chosen in order to evaluate the V-50 for each of the armour styles. The majority of the impacting
velocities fell within the range of 500—600 m/s. When a projectile impacts on the ceramic face of a composite armour, the tip of the projectile is deformed into very tiny fragments [29]. This shattering failure occurs because radial and circumferential stresses exceed the fracture stress at the point of impact [29]. This shattering phenomenon causes a progressive increase of projectile and ceramic contact producing a spreading load on the ceramic face [29].

Figure 4-11 shows an AK-47 bullet before the impact and its retrieved mushroomed steel core (largely stripped of its copper and lead coverings) after impact.

![Bullet before impact](image1)
![Mushroomed steel core after impact](image2)

Figure 4-11: AK-47 bullet and steel core

Figure 4-12 and Figure 4-13 illustrates the work done by Carbajal [2], which shows the comparison between the experiment and the numerical model (ABAQUS) of a bullet impacting steel plate at 253 m/s and 562 m/s, respectively. It can be observed that the damage and failure at various stages during penetration phase cause deformation to the bullet profile, i.e. changes in diameter \((d_1 - d_4)\) and length \((l_1 - l_3)\).
Back Face Signature (BFS) is one of the major parameters used to evaluate the ballistic results for the manufactured armour styles against NIJ Standard 0101.06 (Ballistic Resistance to Body Armour). It is defined as the maximum indentation that is caused in the roman Plastilina clay (grade-1) on which the armour style backing material rests. The BFS is measured with a vernier caliper, which measures the maximum perpendicular depth of indentation into the Plastilina material. The Plastilina top surface is used as a reference point, as shown in Figure 4-14.
4.7 Ballistic testing

The first ballistic tests (trial #1) were carried out, under controlled environment conditions at the Ballistic and Mechanical Testing (BMT) facility, as shown in Figure 4-15, Figure 4-16 and Figure 4-17 presents the layout of manufactured armour styles, test equipment used, chronographs and the armour mounting panel that were used for the ballistic testing. The distance between the barrel and the test specimen was 15 m. Each armour style was mounted on the Plastilina base, held by straps to prevent its movement during ballistic testing.
Figure 4-16: Side view of test apparatus (barrel) used for ballistic testing

Figure 4-17: Chronographs to measure velocity of the projectile

Figure 4-18: Mounting panel for armour styles on Plastilina
4.8 Ballistic test results

In total, 35 armour samples were subjected to ballistic testing. These were manufactured at the DSTO and ADA facilities using commercial materials supplied by ADA. Most of these materials, or their combinations, were proprietary products and the details of their individual characteristic properties and means of manufacture were deliberately not made available. The ballistic performance was used to determine V-50 values for the five different armour styles. Table 4-2 presents all the ballistic test results, while Table 4-3 represents a comparison for the V-50 results. Prior to the ballistic testing, it was initially believed that the SA-1 armour style (consisting only of a clad RSSC ceramic plate bonded directly to the backing laminate manufactured from 16 Kevlar® XPTM layers separated by 15 LLDPE layers bonded together) should present a V-50 that was higher than its comparative armour style.

*Note: the pictures and radiographs for some of the highest, lowest and intermediate velocities for passed ballistic armour styles (trial #1) are shown in Appendices A and B.*

Table 4-3: Results of trial #1

<table>
<thead>
<tr>
<th>Armour style</th>
<th>BA-1</th>
<th>OP-1</th>
<th>OP-2</th>
<th>OP-3</th>
<th>SA-1</th>
<th>Shot #</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>574</td>
<td>F</td>
<td>603</td>
<td>F</td>
<td>607</td>
<td>F</td>
<td>545</td>
<td>P/22</td>
<td>859</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>532</td>
<td>P/22</td>
<td>526</td>
<td>P/25</td>
<td>578</td>
<td>P/31</td>
<td>599</td>
<td>F</td>
<td>708</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>550</td>
<td>P/19</td>
<td>538</td>
<td>P/25</td>
<td>592</td>
<td>F</td>
<td>575</td>
<td>P/26</td>
<td>586</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>589</td>
<td>F</td>
<td>558</td>
<td>F</td>
<td>650</td>
<td>F</td>
<td>556</td>
<td>P/20</td>
<td>528</td>
<td>P/17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>564</td>
<td>P/23</td>
<td>568</td>
<td>P/28</td>
<td>565</td>
<td>F</td>
<td>598</td>
<td>F</td>
<td>553</td>
<td>P/20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>595</td>
<td>P/26</td>
<td>573</td>
<td>P/27</td>
<td>517</td>
<td>P/24</td>
<td>604</td>
<td>P/26</td>
<td>577</td>
<td>P/22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>606</td>
<td>F</td>
<td>601</td>
<td>F</td>
<td>582</td>
<td>F</td>
<td>558</td>
<td>P/20</td>
<td>597</td>
<td>P/22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* P indicates Pass
** F indicates Fail

*Note: during ballistic testing, for armour styles SA-1 Shot #1, SA-1 Shot #2 and OP-2 Shot #4 (in red), the chosen velocities turned out to be considerably higher than the ultimate V-50 performance justified. These three tests gave three significant failures that were better assessed as complements to the results in Section 4.10 and Section 4.11 respectively.*
The penetration mechanism is a complex failure, with the stress wave propagation phenomenon occurring within the ceramic, and these stress waves spread radially outward, causing the ceramic to flex. During impact, when a projectile hits the face of the clad RSSC ceramic plate, its front face is placed into compression, while the rear face is placed under tension.

Table 4-4: Comparison of V-50 results for trial #1

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Basic Armour (BA-1)</th>
<th>Optimum Armour (OP-1)</th>
<th>Optimum Armour (OP-2)</th>
<th>Optimum Armour (OP-3)</th>
<th>Standalone Armour (SA-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest pass</td>
<td>595</td>
<td>573</td>
<td>578</td>
<td>604</td>
<td>597</td>
</tr>
<tr>
<td>Lowest fail</td>
<td>574</td>
<td>558</td>
<td>565</td>
<td>598</td>
<td>586</td>
</tr>
<tr>
<td>Estimated V-50</td>
<td>584</td>
<td>565</td>
<td>572</td>
<td>601</td>
<td>592</td>
</tr>
</tbody>
</table>

Figure 4-19 represents the BFS comparison for the five armour styles. It is clear from the figure that the SA-1 series armour style had a generally lower BFS value at comparative strike velocities than its comparative armour styles. Of the
four impacts on targets SA-1, no BFS value exceeded 22 mm, compared with BFS values of 22 mm to 31 mm across the other armour styles.

Further examinations undertaken from the radiograph of impacted armour styles suggest that clad ceramic plates result in the formation of radial and circumferential crack structures that are symmetrical (refer to Appendix B). The radial cracks are symmetrical generally in pairs, but the circumferential cracks are not continuous across the radial cracks but are at similar radii. The radial cracks are easily visible and are quite prominent under radiograph condition; however, this is not the same for the circumferential cracks. This is because the radial cracks penetrate through the tile thickness as simple bending; giving a perpendicular crack structure that is perpendicular to the face of the tile. The circumferential cracks are of two sorts – simple perpendicular cracks and the spalling cracks that create the cone angle.

4.9 Armour style potting

After the completion of the ballistic tests, some selected armour styles with embedded bullet were chosen for closer examination to analyse and understand the damage to the projectile; RSSC tile and backing laminate (SA armour style). The aim of the potting procedure was to ingress as much low-viscosity resin as possible into the fractured area of the ceramic adjacent to the projectile. Once solidified the armour style was carefully water-jet cut to reveal the cross-sectional view of the RSSC, backing laminate and the impacted projectile. The water jet also cut other regions of interest with minimum disturbance to those regions damaged by the impacting projectile, and with the least loss of material. Figure 4-20 and Figure 4-21 present the resin-encapsulated SA armour style before and after cutting and the water-jet cutter used for this application.
Figure 4-20: Resin encapsulated armour style before water-jet cut (SA-1/04)

Figure 4-21: Resin encapsulated armour style after water-jet cut (SA-1/04)

Figure 4-22: Farley POF 32 water-jet cutting machine

Figure 4-23 shows the section of the selected armour style embedded with the impacted projectile after being water-jet cut. After reviewing this cross section, a few cracks could be observed on the side of the RSSC ceramic plate. This better
revealed details about the extent of crack propagation and the shape and extent of the cone angle formation within the RSSC ceramic tile. It is clear from Figure 4-23 that the full metal jacket (FMJ) of the projectile has been deformed into a mushroom shape and penetration has progressed at a velocity of 528 m/s into the first few layers of the composite. The face of the mild steel core has also been significantly flattened; however, the shape and size of the failure cone in the ceramic are difficult to identify. It is also observed that the impacted projectile has completely penetrated the RSSC tile thickness (4 mm), forcing the pulverised RSSC into the backing laminate but without penetrating deep inside the backing laminate (comprising sixteen layers of Kevlar® XPTM/fifteen layers of LLDPE). Delamination was also observed in the initial layers of backing laminate that were adjacent to the RSSC tile.

![Figure 4-23: Cross-sectional view of the encapsulated SA-1/04 armour style](image)

**4.10 Post-ballistic impact analysis**

Post ballistic impact analysis considered a number of parameters that were seen as important to the characterisation of each impact event, to help in understanding the failure mechanisms that were occurring. The projectile entry and exit hole diameters within the RSSC tile were measured to determine a simple value for the cone angle formation. To achieve this, the clad RSSC tiles were de-bonded from their backing laminates for armour styles SA-1, OP-1, OP-2 and OP-3 and then the woven textile cladding was stripped off by heating in the oven at specific temperature 120°C for a 1 hour time interval. Figure 4-24 represents the de-bonding of the clad RSSC from the backing laminate.
Figure 4-25 represents the uncladding of the ceramic tile to measure the projectile entry and exit hole diameters within the RSSC.

![Figure 4-25: Uncladding of the RSSC ceramic tiles (SA-1/01)](image)

Any retrieved projectiles were carefully examined to assess their shape and damage, and measurements were taken of the retrieved steel core mass, steel core length, steel core diameter and lastly distribution of radial cracks. Figure 4-26 shows the components of the AK-47 projectile and Figure 4-27 represents the steel core dimensions. The details of the projectile or bullet have already been specified in Section 4.5 of this chapter. The steel core was physically measured with vernier calipers to compare the deformation before and after the ballistic test. The length of the steel core was ~ 19.91 mm, the diameter at the end was ~ 5.72 mm and the diameter at tip ~ 3.75 mm.
Note: the projectile or bullet contain a steel core in the centre followed by a lead filler, which is externally covered by a copper jacket.

4.11 Results and analysis

Note: the minimum and maximum values of the x-axis for the following Figure 4-28, Figure 4-29, Figure 4-30, and Figure 4-34 are represented from 500m/s to 900m/s to facilitate easier comparison, especially for SA-1 armour styles. Several earlier shots from the SA-1 batch were fired well above the subsequently determined velocity range of interest. The majority of the remaining graphs have the x-axis covering in range of 500 m/s to 660 m/s.
Figure 4-34 to Figure 4-34 represent the post ballistic analysis for the five armour styles outlined above. Figure 4-28 shows the bullet entry hole diameter in the RSSC ceramic tile. The trend for armour styles OP-1, OP-2 shows that the bullet entry diameter showed increases with increased in velocity; however, armour styles OP-3, BA-1 and SA-1 showed decreases with increases in velocity. The BA-1 armour style has the minimum and maximum entry hole diameter size of 12.4 mm and 16.9 mm within velocity range of 532 m/s to 605 m/s. In contrast, the SA-1 armour style has the minimum and maximum entry hole diameter of 12.9 mm and 19.4 mm within the velocity range of 553 m/s to 858 m/s.

*Note: the BA-1 armour style has 16 loose layers of Kevlar® XP™ as the backing compared to SA-1, which has a composite backing laminate (refer to Table 4-2).*
Figure 4-29: Bullet exit hole diameter vs. velocity (RSSC)

Figure 4-29 represents the exit hole diameter (RSSC). It clearly shows that the armour styles OP-1, OP-2, OP-3 is decreases in size for bullet exit hole diameter with increases in velocity; however, armour styles BA-1 and SA-1 show increases in size for bullet exit hole diameter with increases in velocity. The BA-1 armour style has the minimum and maximum exit hole diameters of 31.2 mm at 574 m/s and 44.5 mm at 595 m/s. However, for armour style SA-1, the minimum and maximum exit hole diameters were 33.5 mm at 597 m/s and 44.1 mm at 708 m/s.
Figure 4-30 represents the ratio of bullet exit to entry hole diameter. The ratio of exit and entry hole diameters is used to determine the cone angle formation (more detail discussed in Chapter 7). The trend for armour styles OP-1, OP-2 and OP-3 shows that the ratio of bullet exit/entry diameter decreases with increases in velocity; however, armour styles BA-1 and SA-1 show increases with increase in velocity. The BA-1 armour style has the minimum and maximum bullet exit/entry hole diameters of 2.25 to 3.45 within velocity range of 532 m/s to 605 m/s. In contrast, the SA-1 armour style the minimum and maximum bullet exit/entry hole diameters of 1.80 to 3.03 within the velocity range of 553 m/s to 858 m/s.
Figure 4-31 represents the retrievable steel core mass. The original mass of the steel core was 4.00 g. The trend for armour styles OP-1 and OP-3 shows the steel core mass increases with increases in velocity; however, armour styles OP-2 and SA-1 show decreases with increases in velocity. The trend for armour style BA-1 is similar to a straight line. The armour style BA-1 has the minimum and maximum steel core mass of 3.60 g at 564 m/s and 3.68 g at 553 m/s. The SA-1 has the minimum and maximum steel core mass of 3.68 g at 553 m/s and 3.63 g at 576 m/s respectively.
Figure 4-32 represents the retrievable steel core length. The actual length measured for the steel core is 19.91 mm. The bullet comprises the steel core; lead filler and copper jacket (refer to Figure 4-10 and Figure 4-11). The trend for armour styles OP-1, OP-2, BA-1 and SA-1 represents that with increases in velocity, the armour style shows decreases in steel core length; however, for armour style OP-3 it shows increases in steel core length with increases in velocity. For armour style BA-1, the minimum and maximum steel core length was 14.63 mm at 595 m/s and 15.87 mm at 564 m/s. For armour style SA-1 the minimum and maximum steel core length was 14.12 mm at 597 m/s and 15.15 mm at 533 m/s.
Figure 4-33: Retrievable steel core diameter vs. velocity

Figure 4-33 represents the retrievable steel core diameter. During the bullet impact, the tip of the projectile is deformed, the lead filler and copper jacket are stripped off. The trend for all armour styles OP-1, OP-2, OP-3, BA-1 and SA-1 shows that the steel core diameter for the retrieved bullet increases with increases in velocity. The armour style BA-1 has the minimum and maximum retrievable steel core diameter of 10.36 mm at 564 m/s and 12.25 mm at 595 m/s. The armour style SA-1 has the minimum and maximum retrievable steel core diameter of 11.36 mm at 553 m/s and 13.2 mm at 597 m/s.
Figure 4-34 represents the distribution of radial cracks on the armour styles, which were physically counted from the radiographs. The trend for armour styles OP-1 and OP-3 shows that the distribution of radial cracks increases with increases in velocity; however, for armour styles OP-2, BA-1 and SA-1, the distribution of radial cracks decreases with increases in velocity. The BA-1 armour style represents the minimum and maximum numbers for distribution of radial cracks as 10 cracks at 589 m/s and 14 cracks at 532 m/s. The SA-1 armour style shows the minimum and maximum numbers for distribution of radial cracks as 11 for both velocities of 708 m/s and 858 m/s and 16 at 528 m/s.

**4.12 Conclusion from first ballistic test (Trial #1)**

During the first ballistic test (trial #1), a series of 7 replicates for each armour style BA-1, OP-1, OP-2, OP-3 and SA-1 were tested for ballistic performance within the confined velocity range of 500 m/s and 604 m/s. The lowest BFS values were observed for the SA-1 armour style, compared to the other armour styles, which is an important parameter as per the NIJ standard. However, the V-50 values achieved for each armour style BA-1 (with 16 loose layers of Kevlar® XPTM), OP-2 and SA-1 (with composite of backing laminate) were 582 m/s, 572 m/s and 592 m/s respectively.
In general, it can be said that none of these armour style performed well when tested for ballistic performance and there is a lot of variability in the presented data. However, there were not enough numbers of samples or replicates to ensure that the results achieved were consistent for each armour style design. In order to justify the results and trends achieved from the first ballistic tests (trial #1), a series of only selected armour styles, i.e. BA-2, OP-2-2 and SA-2, was manufactured for ballistic performance testing. The results and analysis for these selected armour styles will be discussed in detail in the following Chapter 5.
5 Second ballistic test (trial #2)

5.1 Introduction

As mentioned in the earlier chapters the ballistic testing for armour styles (Trial #1) OP-1, OP-2, OP-3, SA-1 and BA-1 was conducted and analysed. Due to the limitations of the number of replicates for each armour styles, a further series of selected armour styles (Trial #2), namely OP-2, BA-1 and SA-1, were manufactured and tested for ballistic performance. In this chapter details of the manufacture and ballistic performance of these selected armour styles, Trial #2, are discussed. These armour styles were manufactured in a similar way as previous armour styles BA-1, OP-2 and SA-1; however, the batch type for the manufactured ceramic (RSSC) was different to that of the previous armour styles, in Trial #1.

*Note: the first ballistic test, second ballistic test and third ballistic test are classified in this thesis as Trial #1, Trial #2 and Trial #3 and they all have the similar areal density across the different sets of manufactured armour styles.*

5.2 Armour styles

Trial #2 consisted of three (3) armour styles that were manufactured for ballistic performance: Basic Armour (BA-2), Optimum Armour (OP-2-2) and Standalone Armour (SA-2), as represented in Table 5-1. The schematic representation of each armour style is shown in Figure 5-1 to Figure 5-3 respectively:

- BA-2 armour style consisted of an RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers)

- OP-2-2 armour style consisted of a cladded RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was bonded using epoxy resin to the front of a backing laminate manufactured from eight layers of Kevlar® XP™ and seven interleaved layers of LLDPE. Behind this backing laminate were eight separate layers of soft Kevlar® XP™ fabric.
SA-2 armour style consisted of an RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was bonded using commercial-grade epoxy resin to the front of a full laminate manufactured from 16 layers of Kevlar® XP™ fabric and 15 layers of LLDPE.

Note: due to the proprietary and commercial-in-confidence nature of this research work, the name of the epoxy resin and the cladding technique used in manufacturing armour styles cannot be disclosed.

Table 5-1: Soft vest and backing laminate details

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Basic Armour BA-2</th>
<th>Optimum Armour OP-2-2</th>
<th>Standalone Armour SA-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile or bullet direction of impact</td>
<td>4 mm RSSC</td>
<td>4 mm RSSC</td>
<td>4 mm RSSC</td>
</tr>
<tr>
<td>Strike face</td>
<td>4 mm RSSC</td>
<td>8 plies of Kevlar® XP™/ 7 plies of LLDPE</td>
<td>16 plies of Kevlar® XP™/ 15 plies of LLDPE</td>
</tr>
<tr>
<td>Backing laminate</td>
<td>NONE</td>
<td>8 plies of Kevlar® XP™</td>
<td>16 plies of Kevlar® XP™/ 15 plies of LLDPE</td>
</tr>
<tr>
<td>Soft vest</td>
<td>16 plies of Kevlar® XP™</td>
<td>8 plies of Kevlar® XP™</td>
<td>NONE</td>
</tr>
</tbody>
</table>
Figure 5-1: Schematic of BA-2 armour style

Figure 5-2: Schematic of OP-2-2 armour style

Figure 5-3: Schematic of SA-2 armour style
5.3 Manufacture of armour styles

As mentioned in Chapter 4, the raw materials to manufacture and ballistic test the armour styles, i.e. woven Kevlar® aramid, Kevlar® XPTM, RSSC tiles, epoxy resin and LLDPE etc. were supplied by ADA. The fabrication of the backing laminate was conducted at the DSTO, ACS-A and RMIT University facilities as shown in Table 5-3. Lastly, the final assembly of the ballistic armour styles was later completed in-house by ADA and involved the following steps:

- cladding a single layer of a woven Kevlar® aramid fabric onto the RSSC strike plate using an epoxy resin
- epoxy resin bonding the backing laminate onto the clad RSSC tile for armour styles BA-2, OP-2-2, and SA-2.

Figure 5-4 to Figure 5-6 present various manufacturing stages of the backing laminate. As mentioned in Chapter 4 and illustrated in Figure 5-4, the backing laminate material was laid on aluminium plate that was covered with release film. The backing laminates were covered with caul plate to provide an equal heat distribution. The caul plate was then covered with a breather, as shown in Figure 5-5. The breather was covered by a vacuum bag film that sealed the aluminium plate around the edges with the help of sealant tape to prevent any air
leaks, as shown in Figure 5-6. Lastly, full vacuum was applied to remove any air content, before the aluminium plate was placed inside the oven.

Figure 5-4: Manufacture of backing laminate

Figure 5-5: Caul plate layout on backing laminate

Figure 5-6: Final layout assembly for backing laminate manufacture
5.4 Ballistic testing

The ballistic tests were carried out in a closed chamber, under controlled environment conditions at the BMT facility. Figure 5-7 represents the series for the OP-2-2 armour style that was used for the ballistic testing. The distance between the barrel and the test specimen was 15 m. The manufactured armour styles were mounted on the Plastilina base, held by straps to prevent their movement during ballistic testing, as mentioned in Chapter 4.

![Figure 5-7: OP-2-2 armour style used for ballistic test](image)

5.5 Ballistic test results

In total, five replicates of three armour styles were subjected to ballistic performance tests. As for Trial #2, these ballistic tests consisted of determining V-50 values for each armour style and Table 5-3 and Table 5-4 presents all the results.

*Note: the pictures and radiographs for some of the highest, lowest and intermediate velocities for passed ballistic armour styles (Trial #2) are shown in Appendices C and D.*
Table 5-3: Results of Trial #2

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Armour Style</th>
<th>Velocity (m/s)</th>
<th>P*/F**</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BA-2</td>
<td>590</td>
<td>P/26</td>
<td>590</td>
<td>P/31</td>
<td>610</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>OP-2</td>
<td>537</td>
<td>P/25</td>
<td>536</td>
<td>P/30</td>
<td>596</td>
<td>P/30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SA-2</td>
<td>580</td>
<td>F</td>
<td>571</td>
<td>P/26</td>
<td>624</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>573</td>
<td>P/31</td>
<td>555</td>
<td>P/29</td>
<td>584</td>
<td>P/29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>566</td>
<td>P/31</td>
<td>589</td>
<td>F</td>
<td>575</td>
<td>P/28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* P indicates Pass  
** F indicates Fail

Table 5-4: Comparison of V-50 results for Trial #2

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Basic Armour (BA-2)</th>
<th>Optimum Armour (OP-2-2)</th>
<th>Standalone Armour (SA-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest pass</td>
<td>590</td>
<td>590</td>
<td>596</td>
</tr>
<tr>
<td>Lowest fail</td>
<td>580</td>
<td>589</td>
<td>610</td>
</tr>
<tr>
<td>Estimated V-50</td>
<td>585</td>
<td>589</td>
<td>603</td>
</tr>
</tbody>
</table>

Figure 5-8 gives the BFS values comparison for Trial #2. It is clear that the SA-2 series armour style had the generally lowest BFS value of 30 mm compared with other armour styles. The maximum BFS value recorded for both OP-2-2 and BA-2 armour styles was 31 mm. The trends for both SA-2 and BA-2 indicate that the BFS value increases with increases in velocity; however, this was not the case for the OP-2-2 armour style.
5.6 Results and analysis

Figure 5-9 to Figure 5-15 present the post-ballistic impact analysis that was conducted on a number of parameters. These analyses help to understand the failure mechanisms that were occurring in Trial #2. The cone angle was calculated by measuring the projectile entry and exit hole diameters within each RSSC tile. To achieve this, the cladding of each RSSC tile was de-bonded and stripped from its backing laminate for OP-2-2 and SA-2 after heating in the oven at 120°C for 1 hour.

*Note: in the first and second ballistic tests i.e. Trial #1 and Trial #2, only 4 mm RSSC ceramic tile was used as an initial strike face with the narrow velocity range confined to 50 m/s to 604 m/s*
Figure 5-9 represents the bullet entry hole diameter in each of the RSSC tiles. For OP-2-2, there appears to be an increase in bullet entry hole diameter with increases in velocity. Of all the armour styles, BA-2 shows the minimum and maximum bullet entry hole diameters, but no trend is seen. SA-2 has the bullet entry hole diameter varying from 13.1 mm to 17.2 mm.

Figure 5-10 represents the bullet exit hole diameter in each of the RSSC tiles. For BA-2, there appears to be an increase in bullet exit hole diameter with increases
in velocity. Of all the armour styles, OP-2-2 shows the minimum bullet entry hole diameters and SA-2 shows the maximum bullet entry hole diameters; however, no trend was observed.

![Figure 5-11: Ratio of Bullet exit/entry hole diameter vs. velocity](image)

Figure 5-11 presents the ratio of bullet exit to entry hole diameters in each of the RSSC tiles. It appears that the SA-2 ratio decreases with increases in velocity. For OP-2-2 the ratio initially increases with velocity; however, it decreases as velocity increases past 589 m/s onwards. The minimum and maximum ratio of bullet exit and entry hole diameter was observed for the BA-2 armour style; however, no trend was observed.
Figure 5-12 presents the retrieved mushroomed steel core mass for each RSSC tile. The original mass of the steel core was 4.00 g. It appears that the SA-2 steel core mass decreases with increases in velocity; however no trend was observed for OP-2-2 and BA-2. The minimum and maximum retrieved mushroomed steel core mass was observed for OP-2-2 and SA-2.

Figure 5-13: Retrieved bullet steel length vs. velocity
Figure 5-13 represents the retrievable steel core length for each RSSC tile. The original steel core length measured was 19.91 mm. The bullet is comprised of the steel core; lead filler and copper jacket (refer to Figure 4-10 and Figure 4-11). Except for one point in the OP-2-2 data set, there appears to be a downward trend in steel core length for all armour styles with increasing velocity.

![Mushroomed steel core diameter vs. velocity](image)

**Figure 5-14: Retrievable mushroomed steel core diameter vs. velocity**

Figure 5-14 presents the retrievable mushroomed steel core diameter for each RSSC tile. The mushroomed diameter measurement signifies the flattening effect of the steel core during its impact on the strike face of the armour. During the bullet impact, the tip of the projectile is deformed, and the lead filler and copper jacket are stripped off, causing a mushrooming effect on the steel core at the point of impact. It appears that the OP-2-2 steel core diameter increases with increases in velocity, but later decreases at 590 m/s. Not much can be said for the SA-2 due to the limited data set and no trend was observed for BA-2.
Figure 5-15 presents the distribution for the number of radial cracks for each RSSC tile, which were measured from the radiographs. When the bullet impacted on the RSSC tile, two types of cracks formed i.e. radial cracks and circumferential cracks (details of these cracks are highlighted in Chapter 7). However, in this analysis only radial cracks are compared, as they can be easily seen from the radiograph images, and the circumferential cracks are not compared. The armour styles OP-2-2 and SA-2 show that the number of radial cracks appears to decrease with increases in velocity; however, for BA-2 the distribution of radial cracks increases with increases in velocity, except for one data point at 580 m/s.

5.7 Conclusion from second ballistic test (Trial #2)

In Trial #2, 5 replicates for each of OP-2-2, BA-2 and SA-2 were tested for ballistic performance within the confined velocity range of 500 m/s and 604 m/s. When the BFS results for Trial #1 and Trial #2 are compared, OP-2-2, BA-2 and SA-2 behave differently to those of OP-2, BA-1 and SA-1 as seen from Figure 5-16 to Figure 5-18 (refer to Chapter 7 for more details). The variation in the results may be attributed to issues related to the cladding of RSSC tiles or due to the RSSC tiles coming from different production batches. In general, it can be
said that none of the armour styles for Trial #1 and Trial #2 stood out as clearly superior in terms of BFS values or V-50 (refer to Table 4-4 and Table 5-4) There is a lot of variability in the data presented that may be attributed to factors other than simply the armour designs and Table 5-4).

Figure 5-16: BFS comparison of OP armours

Figure 5-17: BFS comparison of BA armours
Trial #2 results highlight that the lowest BFS value of 30 mm was observed for the SA-2 armour style, as compared to 31 mm for OP-2-2 and BA-2. There is little difference between any of these Trial #2 armour styles as the BFS ranged from 25 mm to 31 mm across the different velocity range of 500 m/s to 600 m/s. Further details of comparisons between BA, SA and OP-2 armour styles from Trial #1 and Trial #2 will be discussed in Chapter 7.

In order to minimise any further variations, a third series of ballistic tests (Trial #3) was conducted, but using only samples assembled according to BA armour style, i.e. cladding of the RSSC ceramic tile and placing it in front of 16 loose layers of Kevlar® XPTM. Trial #3 was, however, based on testing the ballistic performance of RSSC ceramic tiles with different thicknesses i.e. 4 mm, 6.5 mm and 8 mm, and spanning a far wider velocity range from 300 m/s to 1050 m/s. The details of the assembly and testing of Trial #3 armour styles will be discussed in Chapter 6.

Figure 5-18: BFS comparison of SA armours
6 Third ballistic test (Trial #3)

6.1 Introduction

Chapter 4 provided the details for Trial #1 where armour styles BA-1, OP-1, OP-2, OP-3 and SA-1 were manufactured and tested for ballistic performance. Chapter 5 highlighted the details for Trial #2 where armour styles BA-2, OP-2-2 and SA-2 were manufactured and tested for ballistic performance. In both Trial #1 and Trial #2 ballistic tests, 4 mm RSSC tiles were used as the initial strike face and the strike velocities were maintained within the range of 500m/s to 620 m/s. In this Chapter 6, only Basic Armour styles (BA) were manufactured using three new production batches of RSSC ceramic tiles. Tiles in these batches had thicknesses of 4 mm, 6.5 mm and 8 mm. These BA armour styles were further subdivided into two categories i.e. clad armour styles and unclad armour styles.

Note: the first ballistic test, second ballistic test and third ballistic test are classified in this thesis as Trial #1, Trial #2 and Trial #3 and they all have the similar areal density across the different sets of manufactured armour styles.

The “clad” BA armour styles BA-3, BA-4, BA-5 and BA-6 (T) were manufactured using different thicknesses of RSSC (4 mm and 4 mm-T, 6.5 mm, and 8 mm) to be used as the strike face. The 4 mm RSSC tiles were taken from the same production batch, different from those used for Trials #1 and #2. The strike velocity used to assess ballistic performance for Trial #3 test covered the velocity range from 300 m/s to 1050 m/s in order better understand the behavior and failure mechanisms as compared to the limited velocity range from 500 m/s to 620 m/s for Trial #1 and Trial #2.

The unclad BA armour styles, BA-10, BA-11 and BA-12, were manufactured using different thicknesses of RSSC (4 mm, 6.5 mm and 8 mm) respectively. These were each one-off, with no replicates for each thickness, and the ballistic performance on each was conducted as a single shot rather than across a range of velocities.
Note: the ballistic performance of the unclad armour styles was tested via single shot only to understand the effects of applying the cladding.

6.2 Armour styles

The third ballistic test (Trial #3) contained a series of armour styles with three different thicknesses subdivided into clad and unclad categories. In total 46 armour styles were fabricated; 43 clad and 3 unclad.

6.2.1 Clad armour styles

Four armour styles were manufactured for ballistic testing under the clad category as shown in Table 6-1 and Table 6-2. The schematic representations of BA-3 and BA-6 (T) armour style are shown in Figure 6-1 and Figure 6-2 respectively:

- BA-3 armour style consisted of a 4 mm RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers).
- BA-4 armour style consisted of a 6.5 mm RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers).
- BA-5 armour style consisted of an 8 mm RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers).
- BA-6 (T) armour style consisted of a 4 mm -T RSSC ceramic plate fully clad front and back with a woven Kevlar® aramid bonded with epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers). The term T, indicates tension that was only applied in the x-direction to the textile fabric used to clad the back of the RSSC ceramic, as illustrated in Table 6-1 and shown in Figure 6-2.
Note: Due to the proprietary and commercial-in-confidence nature of this research work, the name of the epoxy resin and the cladding technique used in manufacturing armour styles cannot be disclosed.

Table 6-1: Clad armour styles detail

<table>
<thead>
<tr>
<th>Armour Styles</th>
<th>Basic Armour BA-3</th>
<th>Basic Armour BA-4</th>
<th>Basic Armour BA-5</th>
<th>Basic Armour BA-6 (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile or bullet direction of impact</td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Strike Face</td>
<td>4mm RSC</td>
<td>6.3mm RSC</td>
<td>8mm RSC</td>
<td>4mm RSC T RSCC</td>
</tr>
<tr>
<td>Backing Laminate</td>
<td>NONE</td>
<td>NONE</td>
<td>NONE</td>
<td>NONE</td>
</tr>
<tr>
<td>Soft Vest</td>
<td>16 plies of Kevlar® X³™</td>
<td>16 plies of Kevlar® X³™</td>
<td>16 plies of Kevlar® X³™</td>
<td>16 plies of Kevlar® X³™</td>
</tr>
<tr>
<td>Tension</td>
<td>NONE</td>
<td>NONE</td>
<td>NONE</td>
<td>Only in rear face of clad RSCC</td>
</tr>
</tbody>
</table>
Figure 6-1: Schematic of clad BA-3 armour style

Figure 6-2: Schematic of clad BA-6 (T) armour style
### Table 6-2: Backing laminate and soft vest details (clad armour style)

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Layers of Kevlar® XP™ in the soft vest</th>
<th>Backing Laminate</th>
<th>Number of Kevlar® XP™ layers</th>
<th>Number of alternating LLDPE layers</th>
<th>Number of replicates for ballistic testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Armour BA-3 (4 mm)</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Basic Armour BA-4 (6.5 mm)</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Basic Armour BA-5 (8 mm)</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Basic Armour BA-6(T) (4 mm)</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
</tbody>
</table>

Total number of combinations manufactured 43

#### 6.2.2 Unclad armour styles

Three armour styles were manufactured under the unclad category—Basic Armour (BA-10), Basic Armour (BA-11) and Basic Armour (BA-12), as shown in Table 6-3 and Table 6-4. The schematic representations of unclad armour styles are shown in Figure 6-3:

- BA-10 armour style consisted of a 4 mm RSSC ceramic plate without any clad woven Kevlar® aramid and without any epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers).
- BA-11 armour style consisted of a 6.5 mm RSSC ceramic plate without any clad woven Kevlar® aramid and without any epoxy resin. This was held in front of 16 layers of soft Kevlar® XP™ fabric (not bonded and including no LLDPE layers).
- BA-12 armour style consisted of an 8 mm RSSC ceramic plate without any clad woven Kevlar® aramid and without any epoxy resin. This was
Table 6-3: Un clad armour styles detail

<table>
<thead>
<tr>
<th>Armour Styles</th>
<th>Basic Armour BA-10 Un-Clad</th>
<th>Basic Armour BA-11 Un-Clad</th>
<th>Basic Armour BA-12 Un-Clad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile or bullet direction of impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike Face</td>
<td>4mm RSSC</td>
<td>6.5mm RSSC</td>
<td>8mm RSSC</td>
</tr>
<tr>
<td>Backing Laminate</td>
<td>NONE</td>
<td>NONE</td>
<td>NONE</td>
</tr>
<tr>
<td>Soft Vest</td>
<td>16 plies of Kevlar® XP™</td>
<td>16 plies of Kevlar® XP™</td>
<td>16 plies of Kevlar® XP™</td>
</tr>
<tr>
<td>Tension</td>
<td>NONE</td>
<td>NONE</td>
<td>NONE</td>
</tr>
</tbody>
</table>

Figure 6-3: Schematic of Un clad BA armour style (single shot)
Table 6-4: Backing laminate and soft vest details (unclad armour style)

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>Layers of Kevlar® XP™ in the soft vest</th>
<th>Number of Kevlar® XP™ layers</th>
<th>Number of alternating LLDPE layers</th>
<th>Number of replicates for ballistic testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Armour</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>BA-10 (4 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic Armour</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>BA-11 (6.5 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic Armour</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>BA-12 (8 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total number of combinations manufactured: 3

6.3 Manufacture of armour styles

As for Trial #1 and Trial #2, the raw materials to manufacture and ballistic test the armour styles (i.e. Kevlar® aramid, Kevlar® XP™, RSSC tiles and epoxy resin) were supplied by ADA. The fabrication of all the cladding, especially the cladding in tension (of the rear face) on the RSSC tile, was conducted in-house at ADA facilities. The final assembly of these armour styles was later completed in-house at RMIT University and involved setting up 16 layers of Kevlar® XP™ for the soft vest prior to ballistic testing.

6.3.1 Cladding in tension for RSSC tile

The tension on the rear face of the RSSC cladding for BA-6 (T) was achieved as shown in Figure 6-4. A metal frame with fabric clamps and a stretching mechanism was assembled to lay up the woven aramid, which was un-crimped by applying a tension force in the x-direction only. A resin-coated RSSC tile was mounted on the aramid and was cured under heat and pressure for the designated time (more information in Chapter 7).
6.3.2 Force applied during cladding tension for RSSC tile

The woven Kevlar® aramid was resin impregnated to the rear face of 4 mm RSSC tiles that was tensioned during cladding fabrication, as mentioned in the previous section. The tension was applied to provide extra stiffness to the RSSC tiles to improve their bending rigidity, as the ceramics are good under compression and the Kevlar® aramid is good under tension. The tension was also applied in order to understand and improve the bending extension rate for the RSSC tile. The amount of tension applied on the rear face of the woven Kevlar® aramid during cladding was more than just to un-crimp the woven Kevlar® aramid. The tension applied across the 150 mm x 150 mm RSSC tile was varying from the top to bottom of the tile. However, maximum care was taken such that the applied tension was uniform across the RSSC tiles, although it was not possible at times, due to the loose nature of the woven Kevlar® aramid.

In order to determine how well this tension was applied during cladding fabrication, a series of mechanical tests was conducted for the Kevlar® aramid at the composites laboratory in RMIT University. The extreme ends for the woven Kevlar® aramid were initially resin-coated due to the loose nature of this aramid and to prevent any slippage of the yarns from the jaws during testing. A small section of woven Kevlar® aramid was cut 25 mm wide and 200 mm in length which contained approximately 14 yarns and was subjected to tensile testing as
shown in Figure 6-5 (a). The number of yarns that would cover the area of 150 mm width of a RSSC tile would normally be approximately 84.

The gauge length was kept at 100 mm and the tensile increment was kept at 10 mm/min. Figure 6-6 presents the load extension graph with 4 kN (failure load) for woven Kevlar® aramid. However, when applying tension during cladding for the RSSC tile we estimated the maximum failure load of 24 kN. The data obtained from load extension curve indicated that a tensile force of approximate 7 kN was required to provide pre-tension and approximate tensile force of 1.5 kN to achieve the un-crimp the aramid for a size of 150 mm x 150 mm.

![Figure 6-5: Tensile testing of the woven Kevlar® aramid](image)

(a) Testing machine  
(b) woven Kevlar® aramid after testing

![Figure 6-6: Load extension graph for woven Kevlar® aramid](image)
6.4 Ballistic testing

As before, the ballistic testing was carried out in a closed chamber, under controlled environment conditions at the BMT facility. Figure 6-8 and Figure 6-9 presents the series of clad and unclad armour styles that were tested for ballistic performance. Each replicate was mounted against the Plastilina base, held by straps to prevent its lateral movement during ballistic testing. Since there was no cladding on armour styles BA-10, BA-11 and BA-12 respectively, these tiles were inserted within a plastic bag prior to ballistic performance, as shown in Figure 6-9.
In total, the 46 manufactured armour styles were subjected to ballistic performance within a range of velocities from 300 m/s to 1050 m/s. Apart from the unclad armour styles, the ballistic tests consisted of estimating the V-50 values for each of the different clad and unclad armour styles.
Table 6-5: Results of Trial #3 (clad armour styles)

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
<th>Velocity (m/s)</th>
<th>BFS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>743</td>
<td>F</td>
<td>659</td>
<td>P/27</td>
<td>889</td>
<td>P/26</td>
<td>567</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>722</td>
<td>F</td>
<td>715</td>
<td>P/25</td>
<td>932</td>
<td>P/30</td>
<td>584</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>671</td>
<td>F</td>
<td>765</td>
<td>P/29</td>
<td>993</td>
<td>P/35</td>
<td>456</td>
<td>P/17</td>
</tr>
<tr>
<td>4</td>
<td>637</td>
<td>F</td>
<td>833</td>
<td>F</td>
<td>1047</td>
<td>F</td>
<td>523</td>
<td>P/23</td>
</tr>
<tr>
<td>5</td>
<td>542</td>
<td>P/23</td>
<td>881</td>
<td>P/36</td>
<td>749</td>
<td>P/28</td>
<td>553</td>
<td>P/19</td>
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<tr>
<td>6</td>
<td>517</td>
<td>P/28</td>
<td>942</td>
<td>F</td>
<td>853</td>
<td>P/27</td>
<td>598</td>
<td>P/26</td>
</tr>
<tr>
<td>7</td>
<td>465</td>
<td>P/20</td>
<td>616</td>
<td>P/21</td>
<td>789</td>
<td>P/24</td>
<td>574</td>
<td>F</td>
</tr>
<tr>
<td>8</td>
<td>383</td>
<td>P/20</td>
<td>861</td>
<td>P/34</td>
<td>697</td>
<td>P/19</td>
<td>549</td>
<td>P/22</td>
</tr>
<tr>
<td>9</td>
<td>488</td>
<td>P/23</td>
<td>983</td>
<td>F</td>
<td>1090</td>
<td>F</td>
<td>510</td>
<td>P/20</td>
</tr>
<tr>
<td>10</td>
<td>552</td>
<td>P/28</td>
<td>916</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>594</td>
<td>F</td>
<td>898</td>
<td>F</td>
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<tr>
<td>12</td>
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<td>P/25</td>
<td>728</td>
<td>P/25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>557</td>
<td>P/26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* P indicates Pass  
** F indicates Fail

Table 6-6: Comparison of V-50 results for Trial #3 (clad armour styles)

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>BA-3 (4 mm)</th>
<th>BA-4 (6.5 mm)</th>
<th>BA-5 (8 mm)</th>
<th>BA-6 (4 mm-T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest pass</td>
<td>557</td>
<td>881</td>
<td>993</td>
<td>598</td>
</tr>
<tr>
<td>Lowest fail</td>
<td>594</td>
<td>833</td>
<td>1047</td>
<td>567</td>
</tr>
<tr>
<td>Estimated V-50</td>
<td>575</td>
<td>857</td>
<td>1020</td>
<td>582</td>
</tr>
</tbody>
</table>

Note: the pictures and radiographs for some of the highest, lowest and intermediate velocities for passed ballistic armour styles (Trial #3) are shown in
Appendices E (clad armour) and F (unclad armour). Appendix H presents the retrieved steel cores after ballistic tests at different velocities for clad armours.

Table 6-7: Results of Trial #3 (unclad armour styles)

<table>
<thead>
<tr>
<th>Armour styles</th>
<th>BA-10 (4 mm)</th>
<th>P*/F**</th>
<th>BA-11 (6.5 mm)</th>
<th>P*/F**</th>
<th>BA-12 (8 mm)</th>
<th>P*/F**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot #</td>
<td>Velocity (m/s)</td>
<td>BFS (mm)</td>
<td>Velocity (m/s)</td>
<td>BFS (mm)</td>
<td>Velocity (m/s)</td>
<td>BFS (mm)</td>
</tr>
<tr>
<td>1</td>
<td>549</td>
<td>P/22</td>
<td>488</td>
<td>P/15</td>
<td>870</td>
<td>P/26</td>
</tr>
</tbody>
</table>

* P indicates Pass
** F indicates Fail

Figure 6-10 represents the clad armour styles BFS comparison for Trial #3. It is clearly shown from Figure 6-10 for 4 mm RSSC tile, BA-6 (T) has a lower BFS value than BA-3 at comparable velocities. The results for 4 mm RSSC tile also indicate that by applying tension on the rear face of the RSSC cladding tile, a lower BFS was attained. The results for BA-4 (6.5 mm) and BA-5 (8 mm) armour style signify that they are parallel to each other. It is clearly that shown with increases in velocity for BA-4 and BA-5, the BFS value increases.
Note: in the first and second ballistic test i.e. Trial #1 and Trial #2, only 4 mm RSSC ceramic tiles were used as an initial strike face with the narrow velocity range confined to 500 m/s to 620 m/s to better define and evaluate the V-50 values. However, in Trial #3 different thicknesses of RSSC tile were used with a wider velocity range of 300 m/s to 1050 m/s to better understand the failure mechanism from slow to fast impact.

6.6 Conclusion from third ballistic test (Trial #3)

In Trial #3, 46 replicates for each BA armour style, i.e. clad and unclad were tested for ballistic performance within the velocity range of 300 m/s to 1050 m/s. The 4 mm, 6.5 mm and 8 mm RSSC tiles results for clad and unclad armour styles were compared for BFS values. As discussed in the previous section and outlined in various graphs from Figure 7-15 to Figure 7-21, the unclad armour style only had one replicate for each thickness as compared to the clad armours. The results obtained from these unclad armour styles for different thicknesses coincided well with those of the clad armours. It can be concluded that cladding the RSSC tile does not have any positive or negative implications for the BFS values; however, applying tension on the rear face fabric during cladding does reduce the BFS values.

Figure 6-11: BFS comparison for 4 mm RSSC Trial #3 (clad and unclad)
Figure 6-11 presents the comparison between clad and unclad, 4 mm RSSC tiles with and without tension applied on the rear face cladding fabric. The unclad BFS value obtained from the ballistic performance coincides well with that of the clad armours. The general trend for comparing BA-3 and BA-6 (T) armours is that they are parallel to each other, though at different gradient levels, and BA-6 (T) tends to be lower than BA-3. The BA-10 armour is passing through the BA-6 (T) armour trend; however, the RSSC tile in this is totally deformed to prevent any further shots. By applying tension on the rear face of the cladding fabric, we can see a reduction in the BFS values at comparable velocities between BA-6 (T) and BA-3 armours. It is noticeable that the trends seem to be parallel but displaced. The BFS value varies from 20 mm to 28 mm for BA-3 as compared to 17 mm to 23 mm for BA-6 (T) across the velocity range of 450 m/s to 553 m/s. It can be said that by applying tension in the rear face of the cladding on RSSC tile, the dwell time is increased, and we expect to see a reduction in the BFS value, which is vital to minimising fatalities.

Figure 6-12: BFS comparison for 6.5 mm and 8 mm Trial #3 (clad and unclad)

Figure 6-12 presents the BFS comparison between clad and unclad armours, for both 6.5 mm and 8 mm RSSC tiles. For a given tile thickness, the ballistic
performance of the unclad armour style lies within or on the general trends defined by the clad armours. However, for any subsequent shots on unclad armour, there is not enough material of RSSC tile left to prevent penetration of the projectile, as shown in Figure 6-13. It can be said, that the role of the cladding on the RSSC tile is to hold the radial and circumferential cracks together to prevent penetration from any further subsequent shots.

![Clad and unclad armour style with radial cracks distribution](image)

Figure 6-13: Clad and unclad armour style with radial cracks distribution
7 Results and Discussion

7.1 Introduction

The previous Chapters 4—6 detailed the fabrication and ballistic performance for Trials #1—#3 respectively. In general, various sets of OP, SA and BA armour styles were manufactured and their ballistic performance was evaluated across a range of velocities to determine if any of the armour styles stood out. In this chapter, detailed comparisons for mechanical testing, BFS values, mean cone angles across Trials #1—#3 will be conducted and analysed.

7.2 Mechanical testing

Mechanical tests were undertaken for each woven Kevlar® aramid used for cladding, the Kevlar® XP™ used for backing and the RSSC tiles. The mechanical tests were segregated into two different categories, i.e. compression and tensile tests. The woven Kevlar® and Kevlar® XP™ were both subjected to tensile testing, and RSSC tiles with different combinations of surface coating or cladding (i.e. with resin, with aramid, etc.) were subjected to 3-point and 4-point bend tests to measure the flexure stress and maximum failure load (refer to Chapter 3).

![Graph: 4 mm RSSC strip comparison](image)

**Figure 7-1: 4-point bend tests comparison for 4 mm RSSC**

*Note: D/O stands for different orientation.*
Figure 7-1 and Figure 7-2 represent extension values obtained from the 4-point bend test results for both 4 mm and 6.5 mm RSSC tiles with different cladding combinations, as discussed in Section 3.9.3. It can be seen that the extension of 0.1 mm was obtained for dry RSSC tiles with no surface coatings. When a thin layer of epoxy resin was coated on the rear face of the 4 mm RSSC tile, the failure extension approximately doubled to 0.19 mm. The addition of the woven Kevlar® layer with epoxy resin, on the rear face of the RSSC tile, resulted in an increased extension value of 0.28 mm ~ 0.30 mm depending on the orientation of the woven Kevlar® cladding. When the tension was applied on the woven Kevlar® with epoxy resin, the failure extension values further increased four times from the dry RSSC tiles to 0.41 mm, which decisively showed the effect of tension applied on the rear face of the cladding fabric during fabrication.

For the 6.5 mm RSSC tiles, the extension values for epoxy resin-coated replicates were 0.22 mm. With the inclusion of the woven Kevlar® layer under tension, the extension value increased to 0.49 mm (more than double), which, like the results for the 4 mm RSSC tiles, indicates the beneficial effect of tension applied on the rear face of the RSSC tile during cladding. Unfortunately, due to technical difficulties, no samples were available for the bending test that were
clad only with the epoxy resin and woven Kevlar® layer but without any tension applied. The results for the 6.5 mm tiles were still consistent with equivalently-clad 4 mm tiles. Hazell et al. [63] indicated that brittle materials such as ceramics contain inhomogeneities. As noted in the Figures 7-1 and 7-2, different samples have different extension rates due to their bending stiffness variation which may result in a delay for crack initiation failure mechanism. Geiger [60] indicated that damage to ceramics is augmented by any pre-existing defects that are caused due to shear and the addition of an epoxy resin layer along with the woven Kevlar® assists in delaying the damage to the ceramics by increasing its extension values as shown in Figures 7-1 and 7-2.

In general, it can be said that applying a thin layer of epoxy resin coating delays the crack initiation and propagation effects on the RSSC tile surface. However, when a layer of woven Kevlar® layer is added with and without tension on the rear face of the RSSC tiles during cladding, further improvement in performance can be obtained when compared with dry RSSC tiles. The mechanical test results are consistent with the ballistic test, Trial #3, which showed improvement in reducing BFS values when the tension was applied on the rear face of the woven Kevlar® layer during cladding fabrication.

7.3 Mechanical testing conclusions

The ballistic performance and the interactions between the hard armour and soft vest are a complex phenomenon to understand, as the failure occurs in 10—100 µs. After conducting and comparing the series of mechanical tests as mentioned in Chapter 3, the following conclusions can be made:

- From the 4-point bend tests, the epoxy resin-coated RSSC tiles showed higher failure loads and bending stresses when compared to dry RSSC tiles because the crack initiation failure mechanism was delayed. Applying a coat of resin to the surface of a brittle ceramic significantly improves its bending properties.
- The 4-point bend test using epoxy resin with woven Kevlar® in tension, as discussed in Chapter 3, showed an increase in extension values when
tension was applied on the rear face of the RSSC tiles during cladding fabrication.

7.4 BFS value comparisons

In this section, the BFS values obtained from Trial #1, Trial #2 and Trial #3 are compared in greater detail.

7.4.1 First ballistic test (Trial #1)

![Mean BFS comparison (Trial #1)](image)

Figure 7-3: Mean BFS comparison (Trial #1)

Figure 7-3 presents the BFS comparison for the ballistic performance of Trial #1 armour styles. As mentioned in Chapter 4, the SA armour styles, which are stiffer due to the backing laminate, comprised of 16 layers of Kevlar® XP™ and 15 layers of LLDPE, have the lowest BFS values. The second best ballistic performance was provided by the BA armour style, which only has 16 loose layers of Kevlar® XP™ soft vest and no layers of LLDPE. The Kevlar® XP™ layers in BA were not laminated and were not stiff like those of SA armours.

The OP-2 armour style, which is a combination of 8 layers of Kevlar® XP™ and LLDPE laminated together and 8 layers of soft vest, was only impacted by two shots to estimate the BFS values. As such, the mean BFS values for OP-2 were higher than for OP-1 and OP-3 armour styles. By comparison, all the other armour styles were impacted by four shots. It can be seen from Figure 7-3 that
SA outperformed the other armour styles (within the limits of this experiment) for the mean BFS values at comparable velocities.

![Mean resultant comparison (Trial #1)](image)

Figure 7-4: Mean resultant comparison (Trial #1)

Figure 7-4 presents the retrievable bullet and radial cracks comparison data across all the armour styles for Trial #1. Comparing BA and SA armours, the SA showed higher values as compared to BA armour for each retrieved bullet core length, bullet core diameter and radial cracks at comparable velocities.

It can be concluded from Trial #1, that the SA armour had the lowest BFS values and the highest retrievable results. For the OP armour styles, OP-2 had the lowest retrieved bullet core length and largest bullet core diameter. This was followed by OP-1, which had the maximum number of radial cracks. By comparing the resources used to manufacture these armour styles with different backing stiffnesses, little difference was observed between SA and BA armours, although SA had the lowest BFS values compared to other armour styles.
7.4.2 Second ballistic test (Trial #2)

Figure 7-5: Mean BFS comparison (Trial #2)

Figure 7-5 presents the BFS comparison for the ballistic performance of Trial #2 armour styles. The experimental design of Trial #2 was based on the results obtained from Trial #1, where the SA armour style had the lowest BFS values. However, as can be seen from Figure 7-5, all the armour styles in Trial #2 have almost identical mean BFS values around 28 mm ~ 29 mm. The results obtained from Trial #1, when compared with those of Trial #2, show variability, with the mean BFS values for armours BA and SA from Trial #2 being higher than for their Trial #1 counterparts. However, for the OP-2 and OP-2-2 armours, the results are consistent for both Trial #1 and Trial #2. From the results obtained, it can be seen that BA-2 had the lowest BFS values.

Figure 7-6 presents the retrievable bullet and radial cracks comparison data across all the armour styles for Trial #2. The SA armour style had the lowest bullet core length and highest bullet core diameter. OP had the highest number of radial cracks at comparable velocities compared with BA and SA armour styles. It can be concluded from the mean BFS results obtained that none of these armour styles stand out as a preferred design.
7.4.3 Third ballistic test (Trial #3)

Figure 7-7 presents the results obtained from the ballistic performance for 4 mm RSSC tiles of Trial #3 armour styles. It shows the effects of tension applied to the cladding on the rear face of RSSC tiles across a wide range of impacting velocities.
For 4 mm RSSC tiles, it can be clearly seen that a reduction in the mean BFS values from 24.1 mm to 21.2 mm was achieved at comparable velocities by the addition of tension to the RSSC tile cladding, and a similar trend was also indicated in Figure 6-11. Abkowitz et al [61] mentioned that the front face cladding of armour front face effect on ballistic performance as compared to rear face cladding. During the cladding fabrication, the rear face of the RSSC tile was put into tension for BA-6 (T) armour that resulted in reducing BFS values when compared with the non-tensioned BA-3 armour for the same 4 mm thickness.

![Figure 7-8: Mean BFS comparison (Trial #3)](image)

Figure 7-7 presents the results obtained from the ballistic performance for each 6.5 mm and 8 mm RSSC tiles of Trial #3. However, for 6.5 mm and 8 mm RSSC tiles, the impacting velocities and V-50 values are higher than 4 mm RSSC tiles. The mean BFS values for 6.5 mm and 8 mm RSSC tiles were within the range of 28.1 mm and 27 mm respectively and as such were not significantly different. It should be noted that the mean BFS values are also dependent on impact velocities.

It can be concluded that adding tension on the rear face of the cladding reduces the BFS values, which indicates that the dwell time between the projectile and the armour system has increased. The effects of applying tension on the rear face of the RSSC tile improves the tensile capability of brittle material such as
ceramics when it undergoes bending during impact. As indicated in Figure 7-14, BA-6 (T) armour styles generally appear to have a lower ratio of bullet exit/entry hole diameters as compared to BA-3. Moreover, Figure 7-17 also illustrates that BA-6 (T) showed lower retrievable steel core diameter and lower retrievable steel core length than the BA-3 armour style at comparable velocities.

Figure 7-9: Mean resultant comparison for 4 mm RSSC tiles (Trial #3)

Figure 7-10: Mean resultant comparison for 6.5 mm and 8 mm RSSC tiles (Trial #3)
Figure 7-9 and Figure 7-10 present the retrievable bullet and cracks comparative data across different thicknesses for Trial #3. As seen from Figure 7-9, when comparing the BA-6 (T) and BA-3 armours, by adding tension on the rear face of the RSSC tile during cladding, we can observe a slight reduction in retrieved bullet core length and diameter; however, the number of radial cracks is increased at comparable velocities. As seen from the Figure 7-10, it can be said that when the thickness of the RSSC tile is increased, the mean bullet core length is reduced; however, bullet core diameter and radial cracks increase with increases in thickness.

As highlighted in Section 4.10, the original steel core length was 19.9 mm (approx.). When the projectile impacted the thin 4 mm RSSC tiles, the retrievable bullet core length was within the range of 14.4 mm to 16.5 mm within a comparable velocity range. However, as the thickness of the RSSC tiles increased to 6.5 mm and 8 mm, the retrievable bullet core reduced from 10.8 mm to 7.8 mm respectively. This suggests that more abrasion and deformation occur to steel core at high velocity. Similarly for thin 4 mm RSSC tiles, the retrievable steel core diameter was in the range of 10.4 mm to 12.2 mm; however, when the RSSC tile thickness increased from 6.5 mm to 8 mm the retrievable steel core diameter increases from 14.5 mm to 14.9 mm. The trend for the number of radial cracks for 4 mm RSSC tiles was in the range of 10.8 to 14, although when the thickness of the RSSC tiles increased from 6.5 mm to 8 mm the number of radial cracks increased from 14.1 to 17.1 respectively.
7.5 BFS comparison for Trial #1 and Trial #2

Figure 7-11 presents the variation in the results obtained from the ballistic performance of equivalent armour styles for both Trial #1 and Trial #2. The difference in results obtained, especially for BA and SA armour styles, can probably be attributed to variability in fabrication, testing conditions, cladding technique and RSSC batch types. By comparison, the mean BFS values obtained from the ballistic performance of OP armours are consistent with each other; however, that is not the case for BA and SA armours, which present more variability.

It can be concluded from the results from Trial #1 and Trial #2 that, neither BA nor SA armours have clearly outperformed each other and both of these armour style results showed variability. In contrast the OP armours style showed less variability and the results from both Trial #1 and Trial #2 was consistent. As such, it can be said that in order to maximise the use of resources for these manufactured armour styles, BA armour styles should be fabricated rather than the SA armour style.
7.6 Results and analysis

Figure 7-12: Bullet entry hole diameter vs. velocity

Figure 7-12 to Figure 7-21 present, post ballistic analysis for the clad armour styles, as mentioned in the previous section. Figure 7-12 represents the bullet entry hole diameter in each of the clad RSSC tiles. For BA-3, there appears to be a slight increase in bullet entry hole diameter with increases in velocity. The data points for both BA-3 and BA-6 (T) are very closely comparable and lie in the range of 10 mm – 15 mm. The minimum bullet entry hole diameters for BA-3 and BA-6 (T) are 10.4 mm and 10.6 mm respectively. No significant trend was observed for BA-4 and BA-5 armour styles due to data points being scattered. In general, it can be said, that with an increase in clad RSSC thickness from 4 mm to 8 mm the bullet entry hole diameter increases with increase in velocity from 10.4 mm for BA-3 to 40 mm for BA-5.
Figure 7-13 presents the bullet exit hole diameters in each clad RSSC tile. For 4 mm RSSC tiles, BA-6 (T), shows that the bullet exit hole diameter was slightly lower than for BA-3 at comparable velocities. The minimum bullet exit hole diameters for BA-3 and BA-6 (T) were 28.2 mm and 31.5 mm respectively. No significant trend appears for BA-4 and BA-5. In general, it can be said that with an increase in clad RSSC thickness from 4 mm to 8 mm, the bullet exit hole diameter increases with increase in velocity from 28.2 mm for BA-3 to 71.6 mm for BA-5.
Figure 7-14 represents the ratio of bullet exit to entry hole diameters in each clad RSSC tile. As mentioned in Chapter 4, the ratio of exit and entry hole diameters is used to determine the cone angle formation (more information in Chapter 7). The armour style BA-6 (T) generally appears to have a lower ratio as compared to BA-3 at comparable velocities, except for two data points at 456 m/s and 598 m/s. No significant trend appears for BA-4 and BA-6 as the data set is so scattered. In general, it can be said, that with increase in thickness of the clad RSSC tiles, the ratio of the bullet exit to entry hole diameters reduces with velocity increases from 3.7 for BA-3 to 1.7 for BA-5.
Figure 7-15 represents the retrievable mushroomed steel core masses for each clad and unclad RSSC tiles. The original mass of the steel core was 4.00 g. The armour style BA-3 at 383 m/s shows 7.1 g which must include some contribution from the lead filler and copper jacket. Normally during impact, these soft outer components are fully stripped off. Due to the low velocity, there was not much penetration observed on the armour and little deformation was observed for the bullet. The same can be said for the BA-5 armour style for the velocity of 659 m/s. There was not much difference observed for the 4 mm RSSC tiles i.e. BA-3 and BA-6 (T). In general, it can be said that with an increase in thickness of the clad RSSC tiles from 4 mm to 8 mm, the retrieved steel core mass decreases with increases in velocity. The unclad armour styles are represented as empty diamond shells and they match consistently those of the clad armours.
Figure 7-16 represents the retrievable steel core lengths for each clad and unclad RSSC tile. The original steel core length measured was 19.9 mm. The bullet is comprised of a steel core, lead filler and copper jacket (refer to Figure 4-10 and Figure 4-11). Except for one point in BA-3 and BA-6 (T) shows that the BA-6 (T) has slightly lower steel core length than BA-3 at comparable velocities. This could be due to the application of tension on the rear face in the clad RSSC, which increases the dwell time during the penetration mechanism. In general, it can be said that with an increase in thickness of the clad RSSC tile, the retrieved steel core length decreases with increases in velocity. The unclad armour styles are represented as the empty diamond shells and they match consistently those of the clad armours.
Figure 7-17 represents the retrievable mushroomed steel core diameters for each clad and unclad RSSC tile. The BA-6 (T) shows a lower retrievable steel core diameter than the BA-3 armour style at comparable velocities. During the bullet impact, the tip of the projectile is deformed and eroded and, the lead filler and copper jacket are stripped off, causing a mushrooming effect on the steel core at the point of impact. With an increase in thickness of the clad RSSC tile, the retrieved steel core diameter increases with increases in velocity, resulting in more energy absorption by the RSSC tile. For the 8 mm RSSC tiles, the trend appears to be decreases in retrievable mushroomed steel core diameters with increases in velocity. The unclad armour styles are represented as the empty diamonds and they match consistently those of the clad armours, other than for BA-12 for which we can observe a higher retrievable mushroomed steel core diameter than those of the clad armours.
Figure 7-18 represents the number of radial cracks for each clad and unclad RSSC tile, which were measured from the radiographs. When the bullet impact on the RSSC tile, two types of cracks were formed, i.e. radial cracks and circumferential cracks (details of these cracks are highlighted in Chapter 7). The BA-6 (T) appeared to have a slightly higher number of radial cracks than the BA-3. However, a minimum of 9 radial cracks was observed for BA-3 and a maximum of 13, which is similar to those of BA-6 (T) at comparable velocities. As the thicknesses of the clad RSSC tile increases, the number of radial cracks increases with increases in velocity. The unclad armour styles BA-10 and BA-11 are represented as the empty diamond shells and they match consistently those of the clad armours, although we were unable to retrieve the BA-12 armour style.
Figure 7-19 represents the Plastilina volume displaced for each of the clad and unclad RSSC tiles, at various velocities. This was physically measured with the help of a profiler, which was used to measure the depth and volume profile of the hole within the Plastilina when impacted by the bullet (refer Figure 6-19). During the ballistic tests, the volume of the Plastilina displaced in relation to the velocity kept on changing. The BA-6 (T) had a smaller displacement of Plastilina as compared to BA-3, which can be attributed to the tension applied to the rear face during cladding. The unclad armour styles are represented as the empty diamonds and they match consistently those of the clad armours. It can be said that with an increase in thickness of the clad RSSC tiles, the volume of Plastilina displaced increases with increases in velocity.

Note: during ballistic tests, BFS was measured against a standard starting line to the maximum depth with the help of vernier calipers. However, that maximum depth may not be in the centre of the volume displaced, implying that the bullet stopped off-axis or was skewed.
Figure 7-20: Measuring the Plastilina profile hole after impact (BA-3/11)

Figure 7-21: Plastilina Volume Displaced vs. BFS

Figure 7-21 represents the Plastilina volume displaced for each of the clad and unclad RSSC tiles, compared to BFS values. For all the armour styles, linear relationship was observed, although they were not similar for the BFS values against Plastilina volume displaced, i.e. with an increase in the BFS values, the Plastilina volume increased linearly. For BA-6 (T) a lower BFS was observed as compared to BA-3, resulting in reduced Plastilina volume displaced. The unclad
armour styles are represented as the empty diamonds shell and they match consistently those of clad armours.

7.7 BFS comparison for BA armours (4 mm RSSC tiles)

Figure 7-22: 4 mm RSSC tiles Mean BA BFS comparison (Trial #1—#3)

Figure 7-22 presents the mean BFS comparison for the results obtained from the ballistic performance of only BA armour styles for the 4 mm RSSC tiles Trials #1—#3. It can be seen from Figure 7-22, that the BA-6 (T) armour style has the lowest BFS values when compared with other BA armour styles. By applying tension on the rear face of the woven Kevlar® during cladding fabrication, the dwell time is increased, which shows a reduction in BFS values by 2.9 mm. When compared with BA-2 and BA-3 armours, BA-6 (T) showed significant improvement in performance.

Note: please refer to Appendices A and B for Trial #1 and Appendices C and D for Trial #2. These appendices indicate the highest and lowest velocities for the impacted ballistic armour styles with their radiographs and selected images of Plastilina profiles. There were three different tile batches used for ballistic performance; BA-3 and BA-6 (T) were from the same batch with different velocity ranges.
7.8 Clad and unclad armour styles (Trial #3)

The clad and unclad armour styles were tested for ballistic performance to understand the effects of cladding the RSSC tile. For the clad armour styles a range of impact velocities could be used; however, for the unclad armour styles only a single replicate for each RSSC tile thickness was available for testing. The unclad armour styles in Figure 7-23 are represented as hollow diamonds and they are seen to fit within the range of results for the clad armours. Figure 7-24 presents the BFS Plastilina profiles of the 4 mm RSSC tiles for both clad (542 m/s) and unclad (549 m/s) styles. The advantage of providing cladding is to constrain the radial and circumferential cracks to prevent them from opening and to improve the structural integrity of the armour after the first impact as studied by Ogorkiewicz et al. [59].
It is evident that the BFS values for both clad and unclad armour at these near-equivalent velocities were very close, being 23mm and 22mm respectively. This clearly shows that cladding the RSSC tile has little or no effect on the BFS value in this system and against this threat type. Figure 7-25 shows the radial crack propagation for both clad and unclad armour styles. The cladding of the RSSC tile has been peeled off in the laboratory to reveal the radial crack structure. The bullet exit hole diameter for the RSSC tile was used to indicate the cone angle.

When the projectile hits the clad armour, the cladding material, combined with the layer of epoxy resin, holds the surviving RSSC tile structure together. As
shown in Figure 7-25, if the projectile hits un clad RSSC tile material, little ceramic material remains in place to defend against any subsequent impacts.

If we compare a clad 4 mm RSSC tile with and without tension, we conclude that by applying tension on the rear face during cladding, i.e. BA-6 (T), the BFS values are reduced by 2.9 mm as compared to non-tensioned BA-3. Comparing the effects of different thicknesses for 4 mm, 6.5 mm and 8 mm RSSC clad armours, the BFS trends versus velocity for each armour style look parallel to each other and we observe that with increases in impact velocity, the BFS value increases. However, for unclad armour styles, although we have only a single-shot impact for each thickness, these results fit in well with those for the clad armour styles. It can be said again that, apart from holding the remnant ceramic pieces in place after the impact cladding has little effect unless it is tensioned on the rear face during fabrication of the RSSC tile for this threat type.

In the previous chapter, Figure 7-19 presented the data for the volume of Plastilina displaced with respect to velocity for both clad and un clad armour styles. As with the BFS measurements, the trends for the volume displaced for different thicknesses are also parallel for each thickness type and increase with velocity, as observed in Figure 7-23. Also, Figure 7-21 presented the data for the volume of Plastilina displaced with respect to BFS values for both clad and unclad armour styles. For each of the tile thicknesses (4 mm, 6.5 mm and 8 mm), the relationship with velocity for each armour style is similar but not equivalent, which is consistent with the Figure 7-23 data.

7.9 V-50 comparison

The armour penetration mechanism for the whole system is a complex phenomenon. The velocity at which 50% of the shots penetrate and 50% are stopped by the armour determines the ballistic efficiency or ballistic limit (V-50) of the armour system. This section highlights the V-50 comparisons for Trial #1, Trial #2 and Trial #3.
Figure 7-26: V-50 comparison for Trial #1

Figure 7-26 compares the armour styles used for V-50 performance for Trial #1, where OP-3 had the highest V-50 values compared to OP-1 and OP-2 armour styles. In comparing the SA and BA armours, SA had slightly higher V-50 values. It can be seen that none of the armour styles stand out as having clearly superior V-50 values within the limited data set available. In particular, there is little difference observed between SA and BA armour styles, although they have different stiffness and support conditions behind the RSSC tiles.

Figure 7-27: V-50 comparison for Trial #2
Figure 7-27 presents the V-50 comparison for the Trial #2 ballistic performance. By comparing both SA and BA armours, SA has higher V-50 values, and the same trend was observed for Trial #1. In comparing the results of Trial #2 with Trial #1, it can be said that the BA armour style showed consistent results in terms of V-50 values. However, the SA armour styles showed improvement for V-50 values and OP-2 armour styles improved from 572 m/s for Trial #1 to 590 m/s for Trial #2. This indicates that there is variability in terms of the results obtained, which may be due to the individual ballistic tests or the armour fabrication, etc.

![V-50 comparison (Trial #3)](image)

Figure 7-28: V-50 comparison for Trial #3

Figure 7-28 presents the V-50 comparison for Trial #3 for 4 mm RSSC tile ballistic performance. There was little difference observed between the V-50 values for BA-3 and BA-6 (T) for both armour styles. However as shown earlier in Figure 6-11, applying tension on the rear face of the cladded RSSC tile reduces the BFS values. As expected, when the thickness of the RSSC tiles increases, the V-50 increases as shown in Figure 7-29.
Figure 7-29: V-50 comparison for Trial #3

Figure 7-30: V-50 comparison for 4 mm RSSC tiles for BA armours

Figure 7-20 summarises the BA armour style data sets for all the 4 mm RSSC tiles from Trial #1, Trial #2 and Trial #3. As seen from Figure 7-30, the estimated V-50 values for all three trials for 4 mm RSSC tiles lie within the range of 576 m/s and 585 m/s. Finally, in general, it can be said that for Trial #1, Trial #2 and Trial #3, the V-50 values for BA armour style not significantly different. The V-50 values for OP-2-2 are within the ranges of OP-1 and OP-3 respectively as shown in Figure 7-26.
7.10 Cone angle comparison

This section considers the cone angle comparisons obtained from ballistic performance of three trials across all different thicknesses and various velocity ranges. When the projectile impacted the RSSC tile, its tip became deformed causing the formation of a confined hole (at the point of impact), resulting in the formation of cracks and a cone within the ceramic. Horsfall et al [27] studied the formation of cone angle within the ceramics and mentioned they propagate into the ceramic at 15˚ -65˚. It is during this phase, the momentum of the projectile spreads over a wider area, near the point of impact. The size of the hole on the entry and exit faces of the RSSC tile determines the size of the cone angle, which is dependent on the relative elastic properties of both the ceramic tile and the projectile. The cone angle determined the spread of energy from the impacting projectile over a relatively wider area. Figure 7-31 illustrates the conoid formation within the ceramic tile after different time intervals.

Figure 7-31: Fragmentation of ceramics [3]

Figure 7-32 presents the hole and crack formation on the rear face of a 4 mm RSSC tile for BA-3/01 and BA-3/09 at 743 m/s and 488 m/s velocities respectively. The BA-3/01 shows complete penetration (CP) and BA-3/09 indicates partial penetration (PP) with BFS of 23 mm. Figure 7-33 presents the
hole, cone and crack formation on the rear face of a 6.5 mm RSSC tile for BA-4/01 and BA-4/04 at 659 m/s and 833 m/s velocities respectively. The BA-4/01 had a partial penetration (PP) with BFS of 27 mm, however, BA-4/01 was a complete penetration (CP).

There were different forms of failure observed during ballistic impact, such as formation of radial cracks, and circumferential cracks, as highlighted in Figure 7-32 and Figure 7-33. When comparing 4 mm and 6.5 mm RSSC tiles we observed bigger bullet entry and exit hole diameters, which correspond to bigger cone angles. The damage zone (where the projectile impacts) is conical in shape, with radial cracks initiated at the rear surface and different sized ceramic
fragments are visible during fracturing, as observed by Medvedovski E. [62]. The shearing effects were more prominent and visible with thicker (6.5 mm) rather than thinner (4 mm) RSSC tiles, as shown in Figure 7-32 and Figure 7-33. This shearing or micro cracking occurs in the shallow zone where the tip of the projectile impacts. Frechette et al [30] studied the initial damage to the ceramics in a localized region and indicated the formation of Hertz cracks that coalesce into a conoid. The study conducted by Wilkins [22] indicated that plugging failure is achieved in thick ceramics and petalling failure is achieved in thin ceramics. In the experiments conducted by Van Riet (1987) and referenced by Den Reijer [3] a small amount of ceramic material is left in front of the projectile as it plugs through the ceramic thickness. This form of failure mechanism was observed in 8 mm RSSC tiles.

During the impact of the projectile, formation of radial cracks occurred first, followed by circumferential cracks. Physical analysis of the impact zone resulting in cone angle formation of the cone cracks showed massive friction between adjacent crack surfaces due to shearing of the cone crack propagation. The progressive movement of the rear face of the RSSC tiles near impact zone causes formation of the flaking or stepped shear failure zones as indicated in Figure 7-33.
7.10.1 Trial #1

Figure 7-34: Cone angle vs. velocity (Trial #1)

Figure 7-35: Mean cone angle comparison (Trial #1)

Figure 7-34 and Figure 7-35 illustrate the cone angles obtained from the ballistic performance of Trial #1. From the graphs, OP-3 has the smallest cone angle compared to the other armour styles, and the largest cone angle was obtained for the OP-1 armour style. The variation in the results for the cone angle is due to the different support conditions and stiffnesses of the backing laminate and soft vest, where OP-3 had 4 layers of soft vest and OP-1 had 12 layers of soft vest held in
front of the Plastilina. The BA-1 armour style has a relatively larger cone angle, which means more energy was spread over a wider area as compared to the stiffer SA-1 armour style. In conclusion, it can be said when comparing BA and SA armours that more energy was spread more widely in the case of BA than for the SA armours.

7.10.2 Trial #2

Figure 7-36: Cone angle vs. velocity (Trial #2)

Figure 7-37: Mean cone angle comparison (Trial #2)

Figure 7-36 and Figure 7-37 show the cone angle obtained from the ballistic performance of Trial #2. From the graphs it can be noted that OP-2 has a smaller
cone angle than the BA-2 and SA-2 armour styles. As mentioned in the previous section, there is a bending stiffness difference between SA-2 and BA-2 armour styles and, as observed from the graph below, in this trial, SA-2 had a wider cone angle as compared to BA-2. Comparing the Trial #1 and Trial #2 results for OP, BA and SA armour styles, there is variability in the results obtained due to the complex nature of the penetration mechanism, different batch types for the RSSC tiles and different support conditions. It can be concluded, that BA and SA armours had a bigger cone angle, which signifies that more energy was spread and they are better than OP armours.

7.10.3 Trial #3

Figure 7-28 and Figure 7-39 present the cone angle obtained from the ballistic performance of Trial #3 using different thicknesses of RSSC tiles. It can be observed from the graphs that cone angle formation was dependent on tile thickness, i.e. for BA-4 (6.5 mm) and BA-5 (8 mm) armour styles; the cone angle was reduced with increases in RSSC tile thickness. However, when we compare 4 mm RSSC tile thickness for both normal cladding and cladding with tension, we tend to see an increase in cone angle formation. This suggests that applying tension on the rear face of the cladding increases the spread of energy from the projectile over a relatively wider area.
The ballistic performance for three different trials was tested with various thicknesses and at different velocities. Only one common BA armour style was present within all three trials, although the 4 mm RSSC tiles were manufactured from three different batches. Figure 7-40 presents the BFS comparison for the 4 mm RSSC tiles. By comparing the velocity between the range of 540m/s to
590 m/s, we can observe variation in the BFS values that can be explained by the different RSSC tile batch types, and cladding fabrication. Figure 7-41 presents the comparison for the BA armour style using only the 4 mm RSSC tiles from the same batch (Trial #3) for all the clad and unclad armours, with and without tension applied.

In the previous chapters, it was mentioned that there is variability in the ballistic performance data for clad and unclad armour styles. The variation in these results was attributed to issues related to the cladding of the RSSC tiles or the tiles in the three trials coming from different production batches, as shown in Figure 7-40 and Figure 7-41. In general, by comparing the Trial #3 ballistic performance tests, which used only RSSC tiles from the same production batch, it can be said that by applying tension on the rear face of the cladding on the RSSC tile, the dwell time was increased. We see a reduction in the BFS values, as shown in Figure 7-41. This is vital to minimise fatalities due to blunt trauma injury.

Figure 7-41: BA comparison 4 mm RSSC tiles (Trial #3)
7.12 Ballistic testing conclusions

- The results obtained from Trial #1 with different sets of armour styles (OP, BA and SA) having varying stiffnesses showed that, the SA armour style has the lowest BFS values compared with any counterpart.
- The OP armour style results for the BFS comparison of Trial #1 show that the performance of the OP-1 armour style was in between those of OP-2 and OP-3.
- Trial #2 ballistic results show that all the armour styles OP, BA and SA have similar mean BFS values. When compared with similar armour styles for Trial #1, these results indicate variability in the results due to batch type or manufacturing techniques.
- Trial #3 ballistic results show the effects of applying tension to the woven Kevlar® cladding on the rear face of the RSSC tile, BA-6 (T), which resulted in reduced BFS values when compared to BA-3 at comparable velocities. By applying tension on the woven aramid, i.e. Kevlar® on the rear face of the RSSC tile during cladding fabrication, we observed that a reduction in BFS value of approximate 2.9 mm was obtained. This is a significant result from this preliminary investigation. This reduction in BFS is due to a change in the bending stiffness of the RSSC tile when impacted by the projectile. In general, we are improving the tensile performance of the rear face of the brittle ceramic material.
- The mean BFS values are reduced with increases in the RSSC tile thicknesses as seen from the BA-4 (6.5 mm) and BA-5 (8 mm) armour styles.
- The ballistic results obtained from all the series of Trials #1, #2 and #3 show the variability in terms of manufacturing or testing procedures.
- The ballistic testing showed the effects of the cladding (BA-3), no cladding (BA-10) and modifying the cladding technique [BA-6 (T)] on RSSC tiles to improve the performance of the armour system, i.e. the interdependence of hard and soft armour. The primary role of the cladding is to hold the cracks together and to prevent disintegration of the RSSC tile for any subsequent shots. However, the unclad RSSC tiles provided the same ballistic V-50 results as those of clad armours,
although little RSSC material was left to prevent penetration from any second or subsequent impacts for this system.

7.13 Recommendations for future work

Due to the complex and highly variable nature of this research work, the following recommendations are made:

7.13.1 RSSC tiles

- It should be noted that during manufacturing, care should be taken to fabricate these tiles as consistently as possible, to prevent any batch-type variation in the ballistic performance.
- The surface topography effects of the RSSC tiles should be studied in much more detail and microscopically analysed in order to understand the grain size and grain boundary conditions and the presence of the weak points or micro cracks that can be points of major crack initiation after impact. The surface of the RSSC tile before and after projectile impact should be compared under scanning electron microscopy (SEM) and optical microscopes to understand its failure mechanism.
- The surface of the RSSC tiles should be free from pores and cracks, to delay any initiation of crack propagation or failure mechanism. The primary use of the application of a resin is to delay that crack initiation.
- More work is needed in order to understand the ceramic fragmentation or pulverisation process during the projectile impact and how the fragmentation time (dwell time) may be increased in order to improve ballistic efficiency of the armour system, as mentioned in Chapter 2.

7.13.2 Cladding effects

- The effects of the cladding on the front and rear faces of the RSSC tiles using different aramids with different weave structures needs to be evaluated further.
- The effects of the different grades of epoxy resin and their application also need to be further studied and analysed.
• The effects of resin impregnation on both sides of the front and rear face of the RSSC tiles should be compared and evaluated.
• The tension effects of cladding the front face of the RSSC tile should be studied in relation to the rear face tension effects.
• The tension effects of cladding in both X and Y directions on the RSSC tile should be studied in relation to the rear face while cladding is bonded to the RSSC tile. This may further assist in reduction of the BFS values.
• Work is needed to compare these experimental results with theoretical impact failure models currently being developed by other researchers.

7.13.3 Backing laminate and soft vests

• The orientation effects of the backing material and soft vest layers need further investigation based on the mechanical test results (refer to Chapter 3).
• Evaluation for the soft vest, i.e. the effects on backing laminate as a function of velocity, need to be evaluated to better understand the relationship between soft and hard armour
• More detailed analysis needs to be conducted for the soft vest layers and comparing them with backing laminate at comparable velocities
• The effects of projectile impact during penetration on each individual soft vest layer and its interdependence with other layers during should be studied and evaluated.

Note: Section 1.9 signifies the aim and objectives for the research work. It is shown by this work that the majority of the detailed objectives have met. However, the circumferential crack pattern emanating from point of impact is not carried out in much detail.
8 Appendix A (Trial #1) – Ballistic testing

Figure 8-1: OP-1 armour styles

Figure 8-2: OP-2 armour styles

Figure 8-3: SA-1 armour styles
Figure 8-4: BA-1 armour styles

Figure 8-5: SA-1 armour styles

Figure 8-6: BA-1/02 armour styles impact on Plastilina (532m/s)
Figure 8-7: SA-1 armour styles

Figure 8-8: OP-2 armour styles

Figure 8-9: OP-2/06 armour style
9 Appendix B (Trial #1) – Radiographs

Figure 9-1: OP-1/01 (603m/s) and OP-1/02 (526m/s) armour styles

Figure 9-2: OP-2/04 (650m/s) and OP-2/06 (517m/s) armour styles

Figure 9-3: OP-3/06 (604m/s) and OP-3/01 (545m/s) armour style
Figure 9-4: BA-1/07 (605m/s) and BA-1/02 (532m/s) armour styles

Figure 9-5: SA-1/01 (858m/s) and SA-1/04 (528m/s) armour styles

Figure 9-6: OP-1/02 and OP-3/07 armour styles
Figure 9-7: BA-1/02 and BA-1/04 armour styles

Figure 9-8: Radiographs for SA-1/04 and SA-1/07 armour styles
10 Appendix C (Trial #2) – Ballistic testing

Figure 10-1: SA-2/02 (596m/s) and SA-2/07 (584m/s) armour styles

Figure 10-2: BA-2/04 (573m/s) and BA-2/05 (566m/s) armour styles

Figure 10-3: OP-2/2/01 (590m/s) and OP-2/2/03 (571m/s) armour styles
11 Appendix D (Trial #2) - Radiographs

Figure 11-1: BA-2/01 (590m/s) and BA-2/04 (573m/s) armour styles

Figure 11-2: OP-2/2/01 (590m/s) and OP-2/2/03 (571m/s) armour styles

Figure 11-3: OP-2/2/04 armour style (555m/s)
Figure 11-4: SA-2/02 armour style (596m/s)

Figure 11-5: Side view of SA-2/02 armour style (596m/s)
Figure 11-6: SA-2/04 armour style (584m/s)

Figure 11-7: SA-2/04 armour style (584m/s)
Appendix E (Trial #3) – Ballistic testing (Clad armour)

Figure 12-1: BA-3/01 and BA-3/03 armour styles (4 mm)

Figure 12-2: BA-3/05 and BA-3/08 armour styles (4 mm)

Figure 12-3: BA-4/03 and BA-4/05 armour styles (6.5 mm)
Figure 12-4: BA-4/07 and BA-4/09 armour styles (46.5 mm)

Figure 12-5: BA-5/02 and BA-5/07 armour styles (8 mm)

Figure 12-6: BA-5/08 and BA-5/09 armour styles (8 mm)
13 Appendix F (Trial #3) – Ballistic testing (Unclad armour)

Figure 13-1: Front and rear face of unclad BA-10 RSSC tile (4 mm)

Figure 13-2: Soft vest and Plastilina impact of unclad BA-10 RSSC tile (4 mm)
Figure 13-3: Front and rear face of unclad BA-11 RSSC tile (6.5 mm)

Figure 13-4: Soft vest and Plastilina impact of unclad BA-11 RSSC tile (6.5 mm)

Figure 13-5: BA-12 unclad tile with its effect on Plastilina (8 mm)
14 Appendix G (Trial #3) – Radiographs (Clad armour)

Figure 14-1: BA-3/01 (743m/s) and BA-3/03 (671m/s) armour styles

Figure 14-2: BA-3/05 (542m/s) and BA-3/08 (383m/s) armour styles

Figure 14-3: BA-4/03 (765m/s) and BA-4/07 (616m/s) armour styles
Figure 14-4: BA-5/05 (749m/s) and BA-6/06 (598m/s) armour styles.

Figure 14-5: BA-6/03 (456m/s) and BA-6/06 (598m/s) armour styles.

Figure 14-6: BA-6/04 (523m/s) and BA-6/05 (553m/s) armour styles.
15 Appendix H (Trial #3) – Steel core (after impact)

Figure 15-1: BA-3/01 (743m/s) and BA-3/03 (671m/s) armour styles

Figure 15-2: BA-3/08 (383m/s) and BA-3/05 (542m/s) armour styles

Figure 15-3: BA-6/03 (456m/s) and BA-6/04 (523m/s) armour styles
Figure 15-4: BA-6/05 (553m/s) and BA-6/06 (598m/s) armour styles
References


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