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# Future Armour Materials and Technologies for Combat Platforms

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**ABSTRACT**

The ultimate goal of armour research is to create better armour for battle worthy combat plat forms such as main battle tanks, infantry combat vehicles and light combat vehicles. In each of these applications, the main aim boils down to one of the two things; either reduce the weight without sacrificing protection or enhance the performance at same or even reduced weight. In practice, these ambitions can be fulfilled only if we have with us, appropriate improved armour materials, advanced and innovative technologies and also improved designs, which enable us to use them for creating next generation armour modules. Armour systems have progressed through improvements in metallic, ceramic and lightweight (low areal density) composite materials. Similarly, the advances in development of explosive reactive armour (ERA) and non-explosive reactive armour (NERA) have generated efficient armour system against contemporary high explosive antitank ammunition and missile threats for the armoured vehicles. Yet, to achieve armour performance exceeding that of the current light combat vehicles and main battle tanks, further advancements in armour materials, systems, and survivability technologies are required for new vehicular systems that weigh significantly less than the present combat platforms. Various approaches and advancements in the metallic and composite armour materials, ERA and NERA systems to improve the survivability of armoured vehicles in the futuristic multi-spectral battlefield scenarios are described.

**Keywords:** Steel armour; Composite materials; Combat vehicles; Bulging armour; Reactive protection system

## 1. INTRODUCTION

During the past several years there has been many fold increase in the threat level and the armour materials have, indeed undergone great changes to meet the challenge. There is a need to continue to develop materials and modules which can withstand all futuristic threats. This calls for novel concepts in design and testing methods for optimisation of armour even ahead of the ammunition, to create systems that are protected well. The weight of armour in combat vehicles has always been constrained by the overall weight of the vehicle and the power-to-weight ratio. Changes in the type of threats in recent years have led to a shift in focus on the need for protection against multi-spectral threats. Enormous efforts are being put world over on the development of armour materials and systems to provide greater ballistic protection with minimum weight penalty. For providing such a protection, it is essential to create high performance passive, reactive, dynamic and active armour technologies with creative armour design concepts. Today, no single material is capable of effectively defeating wide range of threats, and hence, a wide variety of armours have to be developed. The most important element of survivability is armour protection. In the beginning, battle tanks were made solely of steels. In recent years the situation has changed with the emergence of excellent armour materials.

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The various types of candidate materials and systems for armour applications namely advance materials like steel armour, polymer matrix composite armour, laminated composite armour, explosive reactive armour, non explosive reactive armour for different types of threats are discussed.

## 2. ROLLED HOMOGENEOUS ARMOUR STEEL (SPADE STEEL)

Rolled homogeneous armour (RHA) steel (Table 1) has remained the standard armour world over on most of the tanks. Its low cost, reliability, availability of production infrastructure, concurrent utility as a structural material and its ease of fabrication have enabled this steel to hold on to its prime position. This steel armour continues to be used in the tempered martensitic microstructure after heat treatment which involves hardening to increase its resistance to penetration by projectiles and then tempering to make it tougher and therefore enhance the energy absorbing capability against impacting projectiles. Also, intense research in ferrous metallurgy has led to greater improvements in the ballistic performance of the steel. Ability to increase its hardness while maintaining adequate toughness has been the key to this success for achieving its high performance. These wonderful advancements have been achieved through micro-alloying, inclusion shape control, and thermo-mechanical processing and grain refinement.

## 3. MEDIUM HARDNESS ARMOUR STEEL

The development of medium hardness steel essentially focused on selection of suitable heat treatment cycles on rolled homogeneous armour (RHA) steel (Table 1) in order to obtain medium hardness with improved ballistic properties and without any cracking tendencies. This approach has advantage of using existing steel and existing production infrastructure making scale up to industrial level practicable. The activities involved are the optimisation of heat treatment on RHA steel in order to get medium hardness, subsequent mechanical property and microstructural evaluation, and ballistic evaluation against small arms and large caliber ammunition. Presently RHA steel is used for the manufacturing of structural parts of battle tanks in India and it has a hardness value of around 300 VHN. This steel was made by Steel Authority of India Limited and supplied in the form of rolled plates. In this work, objective was to enhance the hardness of RHA steel to about 400-450 VHN by employing suitable heat treatment procedures. The targeted hardness is nearly 50 per cent higher than the existing RHA steel being used. While increase in hardness and strength of steel results in improved ballistic properties, it is generally accompanied by a loss in impact properties and weldability[1-2]. Weldability is an important issue since fabrication of structures, armour modules, etc. employ welding extensively for joining. Thus, it becomes essential to optimise processing parameters specially heat treatment to achieve higher hardness and strength without significant loss in weldability.

**Table 1. Chemical composition of RHA steel**

| C | Si | Mn | Cr | Ni | Mo | V | Fe |
|---|---|---|---|---|---|---|---|
| 0.28-0.33 | 0.1-0.25 | 0.4-0.6 | 1.4-1.5 | 1.5-1.7 | 0.4-0.45 | 0.08-0.12 | Balance |

### 3.1 Mechanical Properties

By varying the tempering temperature of RHA steel, a wide range of mechanical properties are achieved. The yield strength and tensile strengths varied in the ranges of 1146 MPa - 1463 MPa and 1247 MPa - 1900 MPa, respectively. The hardness of the steel varies between 381 VHN - 586 VHN. The charpy impact energy varies in the range of 19J - 85 J depending on tempering temperature. Based on the hardness and CVN energy results, two tempering temperatures 450°C and 500 °C are selected which produced a hardness of around 450 VHN coupled with good impact toughness. The mechanical properties of the steel in the as-received condition are compared with the mechanical properties of the steel in the modified tempering condition in Table 2. It can be observed that there is a considerable increase in the yield strength and ultimate tensile strength of the steel at the cost of little ductility in comparison to the presently used RHA steel by adopting modified tempering conditions. The hardness also shows a substantial rise at both the tempering conditions than the presently used steel hardness.

**Table 2. Mechanical properties of RHA Steel at different tempering temperatures**

| Tempering temp. (ºC) | YS (MPa) | UTS (MPa) | % El | Hardness (VHN) | CVN (J) at RT |
|---|---|---|---|---|---|
| 450 | 1380 | 1520 | 13 | 457 | 35 |
| 500 | 1306 | 1450 | 14 | 430 | 44 |
| 650 | 900 | 1000 | 15 | 300 | 90 |

### 3.2 Weldability

Weldability of the modified heat treated RHA steel was evaluated by Tekken tests and results have been found to be satisfactory up to 25 mm thickness in 450 °C tempered condition and up to 80 mm thickness in steel plates tempered at 500 °C. Figure 1 displays the 80 mm thick Tekken test specimen after the welding process. The Tekken test specimens were cut into slices across the thickness for further observation. Figure 2 illustrates the microstructures of 500 °C tempered welded samples of 80 mm thickness plate. No visual cracks were observed. Local critical stress was found to be about 560MPa for 500 °C tempered welded specimens as shown in Fig. 3.

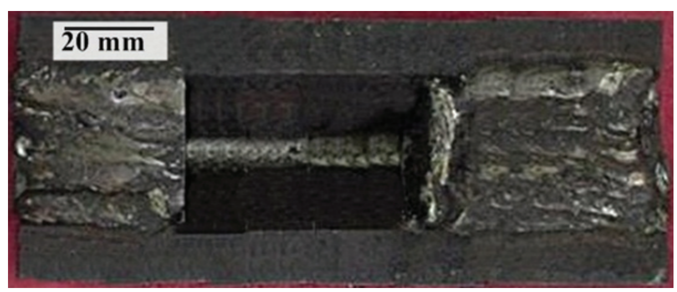
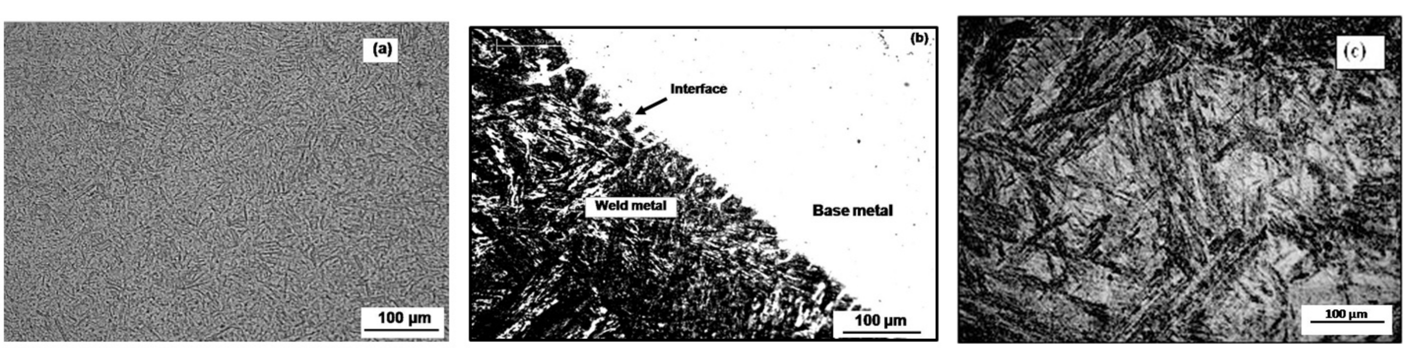



**Figure 1. 80 mm Tekken specimen after welding.**




(a) (b) (c)

**Figure 2. Microstructure of 500 °C tempered 80 mm thick Tekken specimens (a) Base metal, (b) Base metal – weldments interface, and (c) HAZ.**

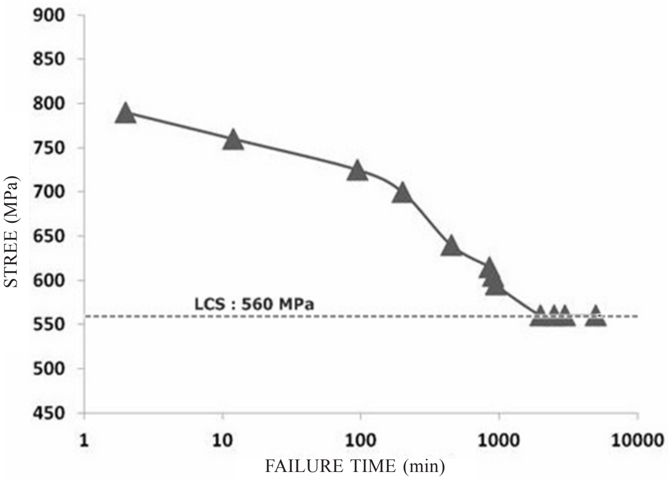



Figure 3. Stress-time curve for 500 °C tempering condition.

### 3.3 Ballistic Performance

The medium hardness steel plates tempered at 500 °C were ballistically tested against 125 mm FSAPDS ammunition (Fig. 4). The large caliber ballistic test results are as shown in Fig. 5 and it can be observed that ballistic performance of the 500 °C tempered plates is approximately 10 per cent - 15 per cent better than the presently used RHA steel plates. Against armour piercing projectiles such as 7.62 AP and 12.7 AP, medium hardness plates showed about 20 per cent - 25 per cent improvement in ballistic performance measured in terms of depth of penetration.

Figure 4. 500 °C tempered steel plates tested against 125 mm FSAPDS ammunition.

## 4. HIGH HARDNESS ARMOUR STEEL: DMR-1700 STEEL

For a given impact velocity, the DOP can be reduced by increasing the hardness and strength of the armour steel. By using high hardness steels, the protection can be increased considerably for a given weight of armour or the weight of the armour can be reduced for a given threat. High hardness steels can be used as components of armour modules fitted in the tanks or can be used as add-on armour for battle tanks. The high hardness steels are therefore going to play an important role in the design of fighting vehicles for improved performance against the kinetic energy threats.

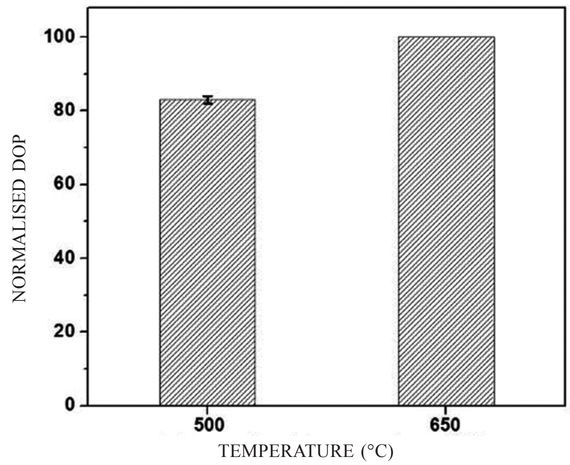



Figure 5. Large caliber ballistic evaluation results.

DMR-1700 steel (Table 3) is a medium carbon low alloy high hardness steel developed by DMRL. This steel has shown promising results for armour application due to its high strength and hardness values. Figure 6 shows the microstructures of the steel plates after heat treatment. Tempered martensitic microstructure is observed in all the plates up to 50 mm thickness. Table 4 displays the comparison of mechanical properties of DMR-1700 steel plates and RHA steel. The strength and hardness of DMR-1700 steel are significantly higher in comparison to RHA.

Table 3. Chemical composition of DMR-1700 steel (wt%)

| C | Si | Mn | Cr | Ni | Mo | Co | Fe |
|---|---|---|---|---|---|---|---|
| 0.33-0.38 | 1.8-2.3 | 0.35-0.65 | 0.8-1.2 | 2.8-3.2 | <1 | <1 | Balance |

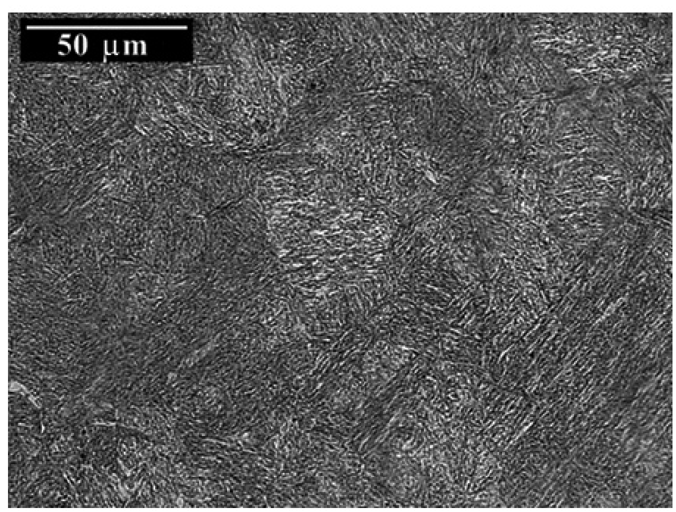



Figure 6. Optical microstructure of 50 mm DMR 1700 steel plate.

**Table 4. Comparison of mechanical properties of DMR-1700 plates with RHA steel**

| Steel | YS (MPa) | UTS (MPa) | Hardness (VHN) | % El | CVN @ RT(J) |
|---|---|---|---|---|---|
| DMR 1700 | 1610 | 1970 | 580 | 11 | 34 |
| RHA | 900 | 1000 | 300 | 15 | 90 |

### 4.1 Ballistic Performance

The ballistic performance of high hardness steel (DMR-1700 steel) has been evaluated against various small arms ammunition as well as against large caliber ammunitions. DMR 1700 steel shows much improved ballistic performance in comparison to RHA. This can be attributed to the high strength and hardness of DMR 1700 steel in comparison to RHA. From the ballistic test it is seen that DMR-1700 steel exhibits improved ballistic performance of about 25 per cent against 7.62 AP ammunition and 20 per cent against long rod kinetic energy projectiles (125FSAPDS) (Fig. 7) as compared to RHA steel.

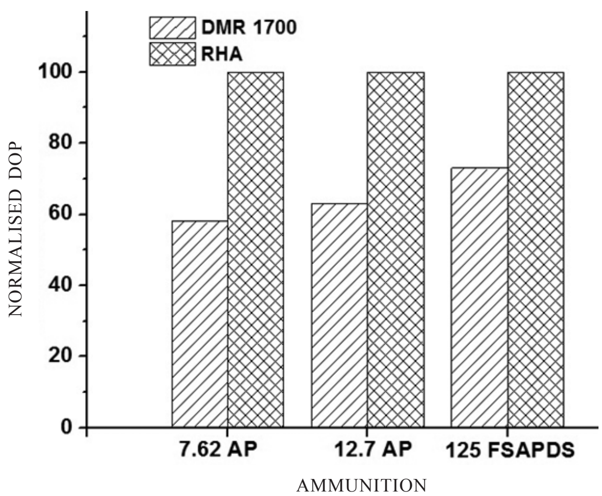



**Figure 7. Ballistic performance comparison of DMR 1700 steel and RHA steel.**

## 5. HIGH NITROGEN STEEL

There has always been a demand to reduce the weight of armoured structures used in various ballistic applications. Weight reduction can be achieved by using newer materials having better ballistic performance or by changing the design of armour systems. Traditionally, high strength low alloy steel with tempered martensitic microstructure has been widely used in various armour applications. Apart from high strength low alloy steels, studies have also been carried out on other class of steels such as secondary hardening steels, auto tempered steels, maraging steels, bainitic steels and nickel free high nitrogen steels (HNS) for potential ballistic applications.

Defence Metallurgical Research Laboratory (DMRL), Hyderabad has recently developed high nitrogen steel (Table 5) for armour applications. High nitrogen steel has been produced industrially at M/s. Jindal stainless (Hisar) limited, Hisar, Haryana, India. The steel plates have been evaluated against various small arms ammunition as well as against large caliber ammunitions. From the ballistic test it is seen that HNS exhibits improved ballistic performance of about 35 per cent against soft projectiles, 10 per cent against armour piercing projectiles and similar performance against long rod kinetic energy projectiles (125FSAPDS) as compared to RHA steel[3].

**Table 5. Chemical composition of high nitrogen steel (wt%)**

| C | Cr | Mn | N | Si | P (max) | S (max) | Fe |
|---|---|---|---|---|---|---|---|
| 0.03-0.06 | 17.5-20 | 17.5-20 | 0.5-0.7 | 0.3-0.7 | 0.06 | 0.015 | Bal |

## 6. GLASS COMPOSITES LAMINATES

Fighting vehicles comprising light weight armour made up of ceramic and polymer composite possess better mobility, fighting ability and fire power as compared to the vehicle with traditional steel armour. From the past two decades glass, aramid and ultra high molecular weight polyethylene (UHMWPE) fibre reinforced composites have gained considerable importance for structural and add-on armour applications due to their high specific strength and high energy absorption under dynamic loads[4-6]. Effect of type of fibre reinforcements such as glass, aramid, carbon and ultra high molecular weight polyethylene (UHMWPE) on ballistic performance was reported. Energy absorption mechanisms of different fiber reinforced composites have been addressed by various researchers through analytical, numerical and experimental studies[7-10]. Though impact performance studies on E-glass/epoxy composites are extensively carried out by various researchers, there is a scanty information available on comparative performance of E-glass/epoxy and E-glass/phenolic composites under high velocity impact especially against 125 mm FSAPDS. Therefore there is need to carry out comparative study on effect of matrix on ballistic performance of glass composite laminates against long rod penetrators.

### 6.1 Ballistic Evaluation

Two different composite laminates namely E-glass/epoxy and E-glass / phenolic laminates were subjected to ballistic evaluation against 125 mm FSAPDS ammunition. Performance of the laminates is compared by measuring the depth of penetration in backing steel plates. Ballistic evaluation was carried out at PXE, Balasore range using 125 mm FSAPDS ammunition with tungston heavy alloy (WHA) penetrator. The penetrator was fired from smooth bore gun of T-72 tank at a impact velocity of 1650±30 m/s. Residual depth of penetration in backing RHA plates was measured. Schematic diagram for measurement of residual depth of penetration in RHA plates is as shown in Fig. 8. Thickness and mass efficiency of the composites were calculated and compared with RHA. Due to the limitations on availability of material only limited no of tests were performed.

Mass and thickness efficiencies for the both laminates have been calculated and as shown in Table 6. From the data, it is observed that both the laminates show approximately similar performance against FSAPDS ammunition with limited ballistic data, phenolic shows slightly better performance but this need

**Table 6. Mass efficiency and thickness efficiency of different glass composites against 125 mm FSAPDS**

| Module | Mass efficiency | Thickness efficiency |
|---|---|---|
| E-glass/Phenolic | 1.17 | 0.61 |
| E-glass/Epoxy | 1.13 | 0.60 |
| RHA | 1.00 | 1.00 |

**Figure 8. DOP test configuration.**

to be verified with more number of experiments. Composites laminates shows better mass efficiency compared to RHA but thickness efficiency is lesser than the RHA. The data suggests that it is required to use appropriate thickness of composites to get the optimum efficiency with respect to mass and thickness of armour modules.

## 7. KANCHAN COMPOSITE ARMOUR

There has been a significant development in the penetration capabilities of kinetic energy (KE) projectiles starting from 1950 to 2000. This development of KE rounds led to drastic increase in the penetration of armour (RHA)[11]. Subsequent design of newer weapons such as shape charge warheads also led to huge increase in penetration in RHA steel. These advances led to the development of improved armour materials as also the designs, since more RHA is needed to provide the increased requirements of protection.

It is now well-known that no single material can provide protection against all types of ammunition which work on quite different principles. Therefore, different materials are combined optimally in the form of composite armour to provide effective immunity. The first composite armour used by British was Chobham armour which consisted of a layer of ceramic between two plates of steel armour[12]. Today, all modern tanks invariably use composite armour in many locations. The performance of composite armour materials can be further improved by choosing the right design. The stacking sequence of the layers is also an important factor in improving its ballistic performance. Composite armour gives protection against most of the ammunitions i.e. K.E and shaped charge ammunitions.

The kinetic energy projectiles deliver momentum on the target and thereby destroy the armour, whereas, the chemical energy weapons produces high velocity jets and cause damage to the armour. Long rod kinetic energy projectiles are used to defeat thick armour plates used in main battle tanks[13]. Hence design of armour should be made such that it can reduce the penetration of the projectile by defeating the same. This reduction in penetration can be achieved by appropriate designing of armour materials. Hence, selection of materials is very essential for design aspect. The properties of the materials should be such that it can blunt the projectile, should dissipate the shock waves generated during impact loading and to absorb the energy of the projectiles by undergoing severe plastic deformation. For blunting of projectile, a hard material such as high hardness steel or ceramic can be used at the front. However ceramic or high hardness materials cannot be used at the front due to their brittle behaviour and thereby losing the integrity of the laminate structure. Rolled homogeneous armour is considered to be a suitable candidate to face the initial impact. DMRL had designed and developed new Kanchan armour modules for improved ballistic performance against large caliber ammunitions by optimising the armour structures for improved protection which can absorb lot of impact energy.

## 8. MATERIALS FOR EXPLOSIVE REACTIVE ARMOUR

Explosive reactive armour (ERA) was developed to defeat shaped charge warheads and found to effectively reduce the penetration. Explosive sheets were sandwiched between two metallic plates which when exposed will be initiated by the impact of the shaped charge. The moving metal plates interact with the jet and cause damage to the jet[14].

The explosive reactive armour contains an explosive layer in between two metal plates. The functioning of explosive reactive armour is governed by two important mechanisms, Jet perturbation and metal cutting effect of the jet[15].

When a shaped charge jet strike the ERA its explosive is initiated within microseconds. Since the detonation products are confined by two metallic plates, they attain velocity and density comparable to that of the jet. These detonation products collide with the incoming jet and the transverse impact of detonation products makes the jet lose its linearity and coherency and there by its penetration power comes down. This mechanism is effective only during a fraction of the total life of the jet. The second mechanism, metal cutting effect is caused by the interaction of the moving plate with the jet. The plate moves laterally with respect to the jet direction exposing new surface to the incoming jet, which causes the consumption of the jet[16].

Defeat of long rod penetrators by explosive reactive armour occurs by breaking of the projectile by the moving plates. Breaking of the projectiles needs high strength flyer plates. The lateral movement of the plate with respect to the projectile consumes the projectile and reduces the penetration power. Defeat of long rod projectile needs not only high strength but also an optimum toughness so that the plate will not disintegrate and stay continuous during the flight which is critical for the performance.

Recently explosive reactive armour has been developed with hard armour steel plates to defeat shaped charge and to reduce the penetration of long rod projectiles.

High strength armour steels have been developed for use in explosive reactive armour. These steels are tempered martensitic steel. The steel plates were tempered at different temperatures such that the resulting mechanical properties will suit the requirements. They were used as part of ERA sandwich structure. The ERA developed have resulted in 80 per cent reduction in the shaped charge penetration (Fig. 9) and around 30 per cent reduction in the long rod penetration in RHA.

**Figure 9. Experimental set up for ballistic evaluation of ERA against shaped charge warhead.**

## 9. MATERIALS FOR NON-EXPLOSIVE REACTIVE ARMOUR

Non explosive reactive armour (NERA) sandwiches are attractive in add-on-armour applications. NERA is also called bulging armour. While explosive reactive armour sandwiches are known to be extremely effective against shaped charge jets, they have inherent disadvantages such as those caused by undesired interaction of the flying plates with the main armour and the environment. To overcome the significant safety drawback posed by the explosive content of reactive armour, inert cassettes containing metallic sandwiches with inert filling materials were proposed by Held[16] and Lundgren[17], *et al*. Jet-metal interaction involving momentum exchanges in a direction transverse to the jet motion are considered to be the basic cause for jet disruption in a reactive armour[18]. Figures 10 shows the basic working principle of non explosive reactive armour. Difference in the energy content is the main feature that distinguishes inert cassette from the reactive sandwich.

Due to significant safety advantage, development of non explosive reactive armour (bulging armour) has been pursued at DMRL. Recent DMRL results of NERA against HEAT missile have shown that NERA can reduce more than half of the penetration of HEAT missile when compared to its penetration in monolithic RHA steel plate[19]. Figure 11 shows photographs of the test set up and bulging armour panels before and after penetration.

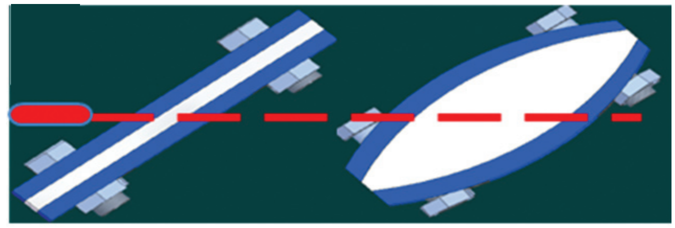


**Figure 10. Working principles of non explosive reactive armour.**

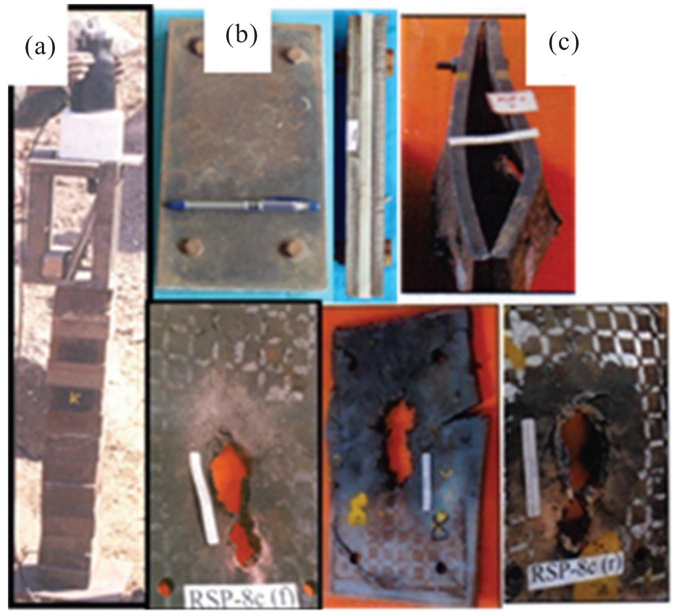



**Figure 11. (a) Photographs of the test set up for firing of NERA against shaped charge warhead and bulging armour panels (b) before and (c) after penetration.**

## 10. CONCLUSIONS

The strength and hardness of the currently used RHA steel are increased substantially, to 1380 MPa and 450 VHN respectively by adopting suitable heat treatment procedures. Weldability of the medium hardness steel has been found to be satisfactory up to 80 mm thickness in steel plates tempered at 500 °C. The medium hardness steel displayed around 10 per cent - 15 per cent improvement in ballistic performance over currently used RHA steel. DMR-1700 steel plate's shows good combination of strength and impact toughness. There is a significant improvement in ballistic performance of the high hardness steel compared to RHA steel. Due to better ballistic performance and lower cost, high nitrogen steel has potential to replace RHA (SPADE) steels in armour modules and add on armour structures. Significant weight saving can be achieved in armour solutions which are primarily used against deformable projectiles by using HNS in the place of SPADE steel. In case of armour solutions against armour piercing and long rod projectiles, application of HNS in place of SPADE steel will result in significant cost reduction.

Ballistic performance of laminated composite against 125mm FSAPDS residual depth of penetration shows similar for epoxy and phenolic based composite laminates. The study shows type of resin is not affecting on ballistic performance of E-glass composite laminates when it is subjected to 125mm FSAPDS ammunition. Laminate ballistic performance has been compared with RHA and found that mass efficiency is better than RHA whereas thickness efficiency is inferior to RHA plates. Kanchan composite armour can provide protection against kinetic energy projectiles as well as chemical energy based shaped charged projectiles.

High strength armour steels have been developed for use in explosive reactive armour. The ERA developed has resulted in 80 per cent reduction in the shaped charge penetration and around 30 per cent reduction in the long rod penetration in RHA. NERA can reduce more than half of the penetration of HEAT missile when compared to its penetration in monolithic RHA steel plate.

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## CONTRIBUTORS

**Mr B. Bhav Singh** obtained his MTech (Metallurgical & Materials engineering) from the Indian Institute of Technology Madras, in 2004. Currently he is working as Scientist E at Armour Design and Development Division, Defence Metallurgical Research Laboratory, Hyderabad. His research interests are in the areas of development of steel, titanium armour, bulging armour.
In the present work, he has carried out the experimental studies on high hardness steel, medium hardness steel, high nitrogen steels, bulging and preparation the manuscript.

**Mr G. Sukumar** obtained his MTech (Metallurgical and Materials engineering) from the Indian Institute of Technology Madras, in 2009. Currently, he is working as Scientist-C at the Armour Design and Development Division, Defence Metallurgical Research Laboratory, Hyderabad. His research

interests are in the areas of development of steel, titanium armour and bulging armour.
In the present work, he was involved in the experimental studies on high nitrogen steels, bulging armour and writing manuscript.

**Mr P. Ponguru Senthil** obtained his MTech (Metallurgical and Materials engineering) from the Indian Institute of Technology Madras, in 2016. Presently he is working as Scientist-D at the Armour Design and Development Division, Defence Metallurgical Research Laboratory, Hyderabad. He is involved in the development of armour steel plates for advanced explosive reactive armour and medium hardness armour steel development.
In the present work, he was involved in the experimental studies on explosive reactive armour.

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In the present work, he was involved in the development of high hardness armour steels, medium hardness steels and their weldability studies.

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In the present work, he has carried out the experimental studies on composites armour.

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In the present work, he was involved in planning of work and arranging various materials and systems required for experiments.

**Dr Vemuri Madhu**, obtained his PhD (Applied Mechanics) from IIT Delhi, in 1993. Currently, he heads the Armour Design and Development Division, Defence Metallurgical Research Laboratory, Hyderabad. He is working in the areas of development of armour materials and systems for various types of protective applications. His research interests are : Ceramic and composite armour development, modelling and simulation of ballistic phenomena, high strain rate, shock and blast studies.
In the present work, he was involved in design of experiments and analysis of test results.

**Dr G. Madhusudhan Reddy** obtained PhD (Metallurgical Engineering) from Indian Institute of Technology, Madras, in 1999. Presently he is working as Scientist 'H' and heading the Metal Joining Group of Defence Metallurgical Research Laboratory, Hyderabad. He has more than 300 scientific publications to his credit.
In the present work, he has carried out the weldability studies of different armour materials such as high hardness steels and medium hardness steels.