1. Introduction

The word armour originates from the French word armure which means arms and equipments. Armour is a means of protection that is used to prevent damage to an object, individual or vehicle by weapons or projectiles. In a battle field, personal armour is needed to provide protection for soldiers against small arms and fragments. In case of combat vehicles protection is required to withstand the impact of shrapnel, bullets, missiles or shells to protect the personnel inside from enemy fire. Combat vehicles where such protection is required include different infantry combat vehicles, tanks, aircrafts and ships. The application of armour is also extended to provide protection in civilian vehicles. These vehicles include cars used by important personalities and for officials working in conflict regions. Armoured vehicles are used during transfer of money and other valuable items to reduce the risk of robbery. Spacecrafts need amour for protection against impacts from micro meteoroids in space. In modern aircrafts armour is employed around the fan casing of turbine engines to prevent damage to the airframe in case of breaking of a turbine blade.

1.1. Historical background

Armour has been employed throughout the history of mankind. In Europe the Roman legions utilized different types of armour (Laible and Barron, 1980). In medieval age full steel plate harness armour is used for protection. In Japan the samurai warriors utilised many types of armour for hundreds of years constructed from iron plates. The Chinese used metal plates for protecting important body parts. Soldiers in the American civil war employed iron and steel vests for protection.

Armour has been made from a variety of materials, beginning with leather and evolving through metal plates in to different composites (Laible and Barron, 1980). The ancient chainmail was made of interlocking iron rings. Gradually, small additional plates or discs of iron were added to provide protection to vulnerable body parts. At the same time, hardened leather was used for protecting arm and leg pieces. Subsequently, the plate armour was invented. This was made of large iron plates sewn inside a textile or leather coat. Today ballistic vests are made up of different high strength polymers, ceramic or metal plates. High strength steels, aluminium alloys and combination of ceramic and metals are used for the protection of present day combat vehicles.

1.2. Armour materials

The materials used in the fabrication of armour can be classified in to two broad groups i.e. metals and non-metals. Such a classification is shown in Fig. 1.1. Metallic armour consists of steel, aluminium alloys, titanium alloys, magnesium alloys etc. Whereas non-metallic armour consists of different types of polymers, glasses, ceramics, and composites.

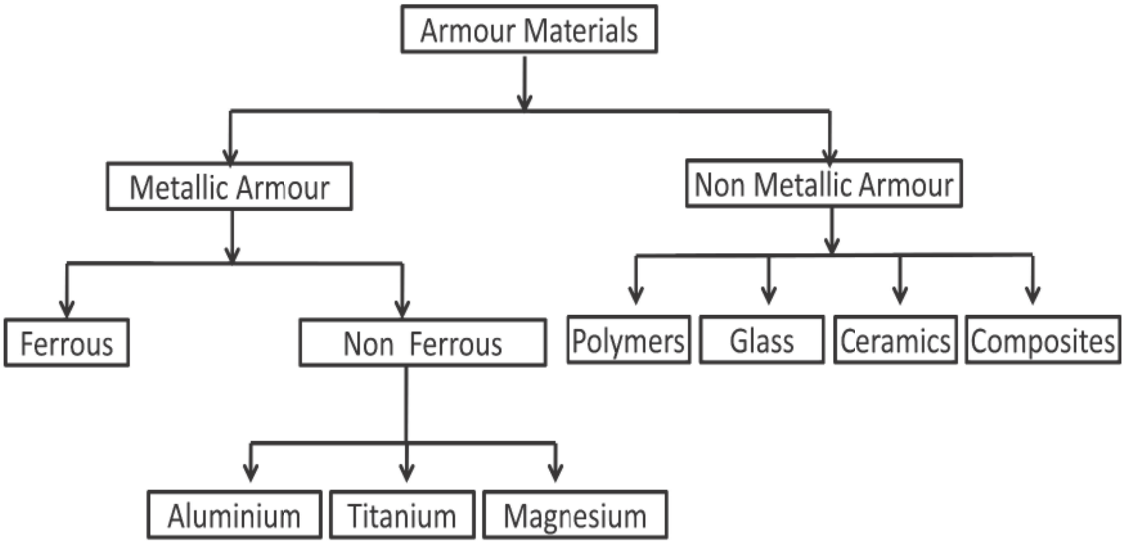


Fig. 1.1: Classification of armour materials.

1.2.1. Metallic armour materials

The role of metals in the history of armour materials is quite vast (Papetti, 1980). Metals have always received special consideration in the development of armour protective systems for many reasons namely availability, ease of fabrication, flexibility and cost. Metals are continuous, homogeneous materials with negligible micro defects and ductile in nature with a high level of fracture toughness. Metallic armour is very good in resisting cracking, spalling and fracture upon multiple impacts while maintaining the structural integrity. Also, metals can display different properties to meet different threats through alloying, heat treating or other processing techniques. Metallic armour is either ferrous or nonferrous and is produced by rolling, forging or by casting. Rolling and forging are employed to produce plates while casting is used to produce special shapes such as tank turrets, etc. Metals of different hardness are interwoven by various methods to produce dual property armour. Ferrous armour comprises of different grades of high strength steels. In non-ferrous metals aluminium, magnesium and titanium alloys are used in armour applications.

1.2.2. Non-metallic armour materials

There is an increase in the role of non-metallic armour materials in recent times. Laminated glass layers built from glass sheets are utilised in bullet resistant applications. Different ceramic materials are used for their low density and high hardness. Ceramics are very effective against defeating shaped charge ammunitions. Composite armour consists of layers of two or more materials with significantly different physical properties and is effective against kinetic energy as well as shaped charge ammunitions.

1.3. Threats for armour

The armour has to protect against different kinds of ammunitions in the battle field. The ammunitions can be divided as small, medium and large caliber ammunitions on the basis of the caliber of the gun. The range in caliber from the 5.56 to 14.5 mm comprises of small arms ammunition. From caliber range 20 to 40 mm are called medium caliber ammunition and beyond 40 mm are known as large caliber ammunition. Small arms ammunitions with a lead or soft steel core are known as ball ammunition and are used against personnel (Fig. 1.2a). Small arms ammunitions with a hard steel core are called armour piercing ammunition (Fig 1.2b). Medium and large caliber ammunitions are primarily used against armoured vehicles. High strength steels, ceramics and different composites are used to provide protection against medium as well as large caliber ammunitions. Whereas steel, aluminium alloys are used against small caliber ammunitions.

Fig. 1.2: 7.62mm small arms ammunitions (a) ball ammunition and (b) AP ammunition with its hard steel core(Crouch, 2016).

1.4. Properties required for armour materials

For better ballistic resistance the armour material is expected to perform its function in two ways:

i) To absorb the impact energy of the projectile
ii) Make the projectile to absorb the impact energy on itself

Metallic armour materials absorb the impact energy of the projectile through plastic deformation. The total energy absorbed by the material is given in Equation 1.1 (Bhat, 1985).

$$E = \sigma \varepsilon V \text{ ------ } 1\ .1$$

Where E = energy absorbed, σ = flow stress, ε = strain, V = volume of material participating in energy absorption. The energy absorption by the armour material can be improved by increasing the strength of the material and spreading of the deformation zone during penetration process. It is essential for the armour material to sustain the large strain gradients produced during ballistic impact without formation of cracks. This is possible when the material deforms in a homogeneous manner during projectile penetration process. Higher ductility of the material is important in this regard. The spread of the plastic deformation can be increased by increasing the impact toughness of the material.

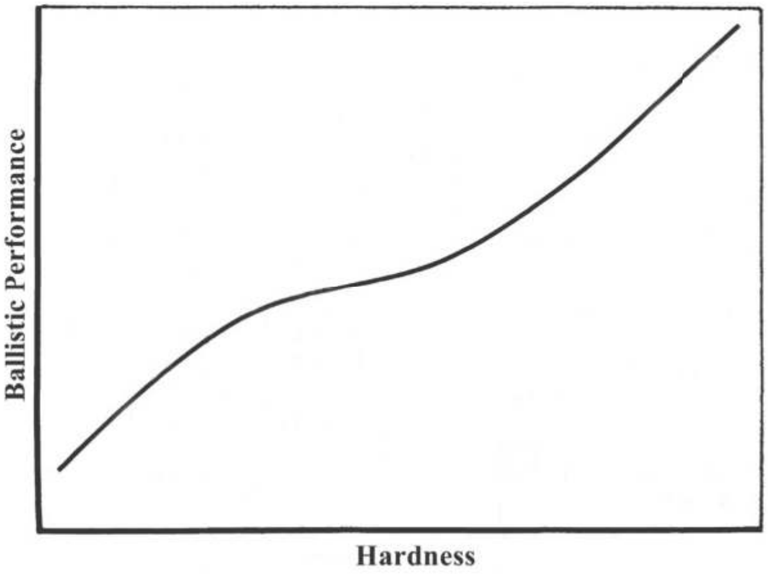


Fig. 1.3: Relationship between hardness and ballistic performance(Papetti, 1980).

The relationship between armour material hardness and strength with ballistic performance is illustrated in the Fig. 1.3 (Papetti, 1980). Enhancing the hardness of the armour material induces high compressive stress on the projectile during penetration. The compressive stress waves travel across the projectile and reflect back as tensile waves. The projectile breaks down into smaller pieces due to the interaction of compressive and tensile stress waves. The smaller pieces possess much lower impact energy than the complete projectile and hence a reduction in the penetration ability of the projectile. This improves the ballistic performance of the armour material.

The shape of the small caliber projectiles when stopped successfully by the armour plate is exhibited in Fig. 1.4 (Crouch, 2016). The ball projectiles get deformed whereas the armour piercing projectile breaks in to small pieces.

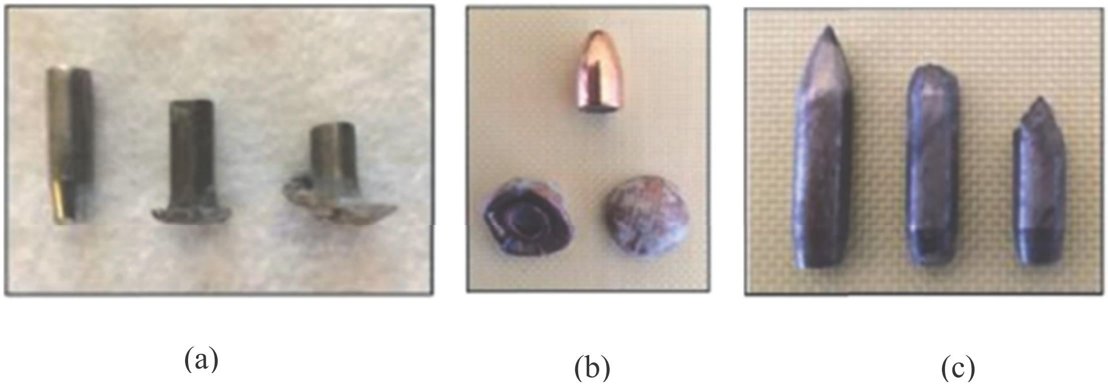

(a) (b) (c)

Fig. 1.4: Shape of the projectiles upon stopped by the armour plate; (a) deformed mild steel projectiles, (b) deformed lead projectiles and (c) broken high hardness projectiles (Crouch, 2016).

1.5. Failure modes observed in ballistic impact

There are different types of modes of failure observed during ballistic impact. It is fundamentally important to understand the possible failure modes when developing improved armour materials and armour systems.

1.5.1. Ductile hole formation:

This mode of failure is observed in target plates impacted with pointed kinetic energy projectiles and is considered to be an efficient energy absorbing mechanism. The pointed projectile creates a hole in the target plate through plastic deformation and displacement of the material (Fig. 1.5). The target plate material flows outward radially from the nose of the projectile and the material ahead of the projectile gets pushed to form a bulge in the rear of the target. In the entry side of the target plate petals of fractured metal are formed.

1.5.2. Plugging

Plugging type of failure mode is observed in the target plates when impacted with a blunt nose projectile (Fig. 1.6). During impact, the material ahead of the projectile moves while the rest of the target remains relatively stationary. It results in a local compression of the material ahead of the projectile and shear deformation in narrow shear bands.

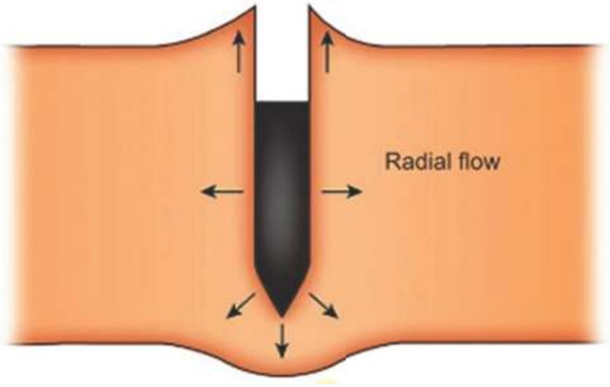


Fig 1.5: Schematic of ductile hole formation(Crouch, 2016).

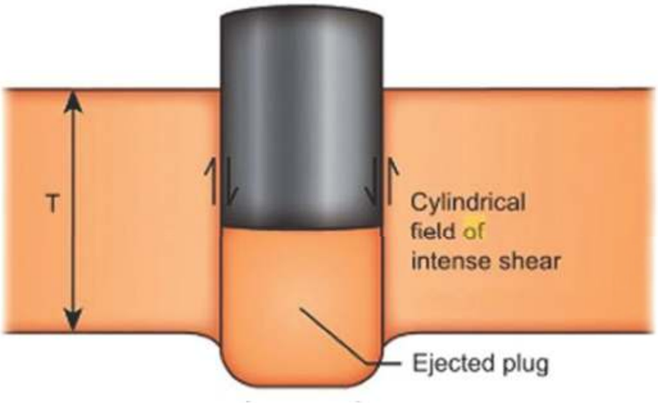


Fig. 1.6: Schematic of plugging process (Crouch, 2016).

1.5.3. Discing

This is a rear face spalling observed in targets subjected to high velocity impact and it occurs as a result of intense bending stress created in the target (Fig. 1.7). It is caused by a fracture event taking place late in the penetration process.

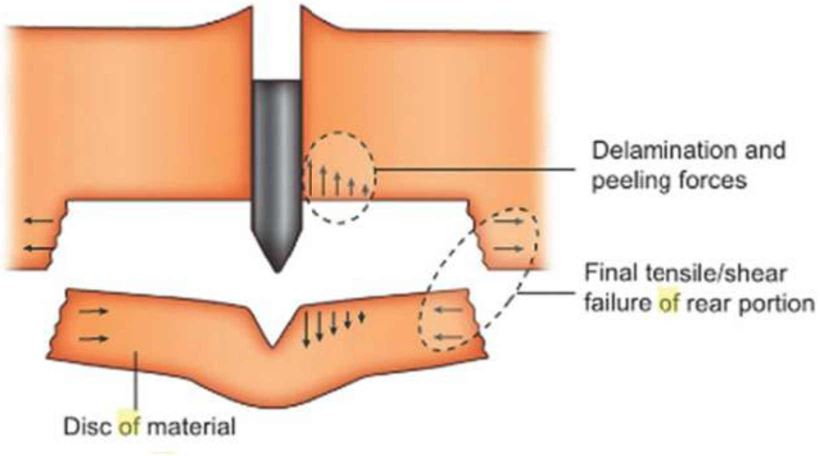


Fig. 1.7 : Schematic of discing process(Crouch, 2016).

1.5.4. Spalling

This is a metallic surface failure observed during ballistic impact in which the metal is broken down into small flakes (spalls) from a larger solid body (Fig.1.8). This process occurs due to the interaction of tensile and compressive shock waves during penetration.

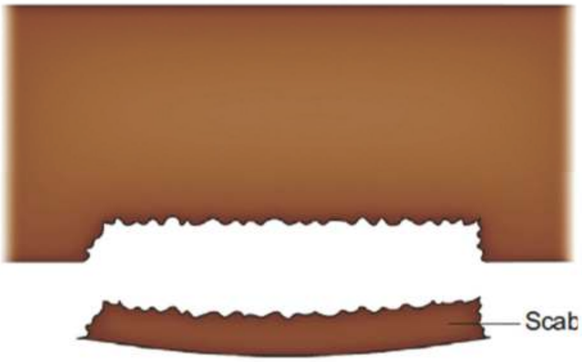
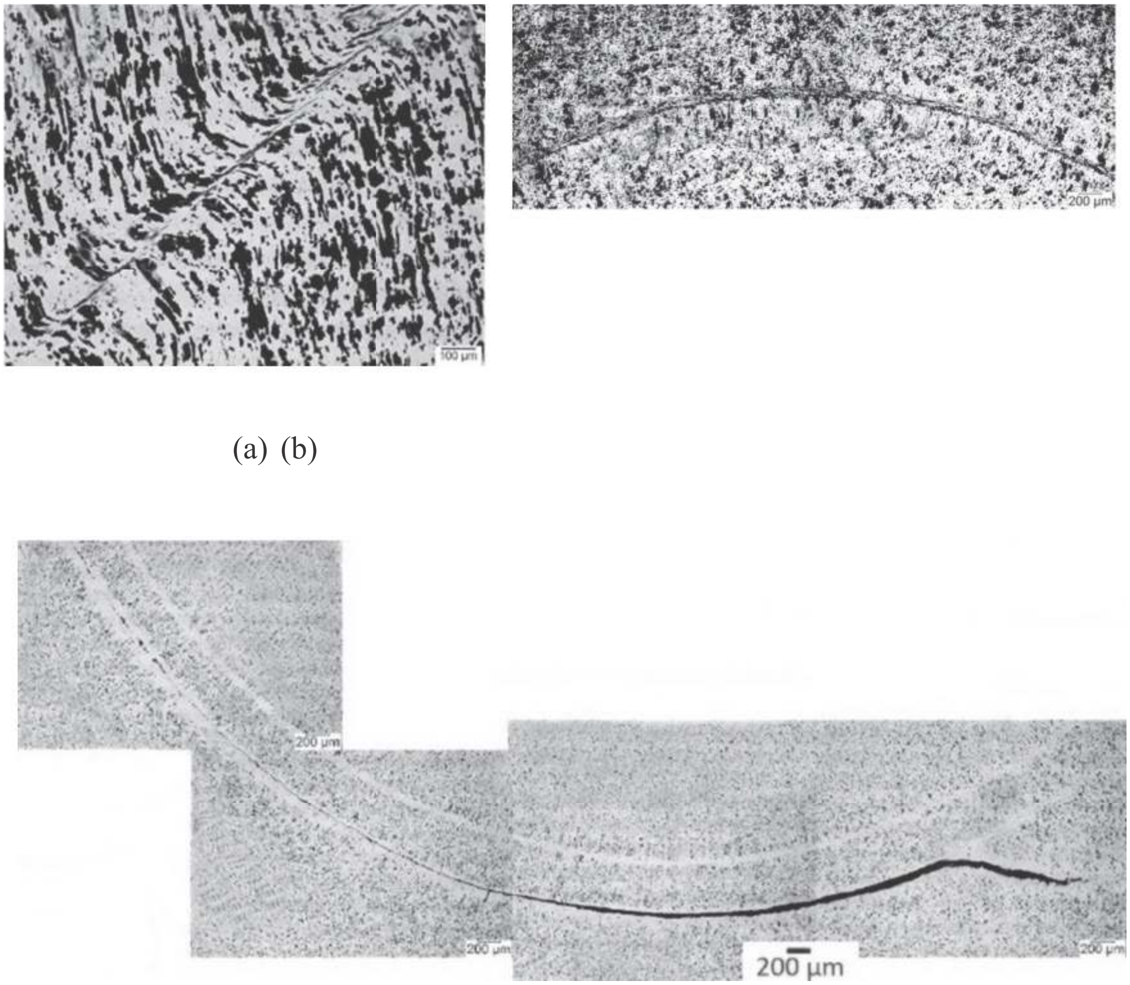


Fig 1.8 : Schematic of spalling process(Crouch, 2016).

1.6. Adiabatic shear bands

Adiabatic shear bands (ASBs) are zones of intense shear deformation describe the localization of plastic flow that occurs when metals are deformed at high strain rates(Timothy, 1987). Formation of ASBs is attributed to the destabilizing effect of therma1 softening which outweighs the effects of strain rate hardening in a deforming region when the local rate of heat generation resulting from the plastic flow exceeds its rate of dissipation into the surrounding material. It has been mentioned that ASB formation takes place when the shear strain localization leads to a critical strain and strain rate (Xu et al., 2008).



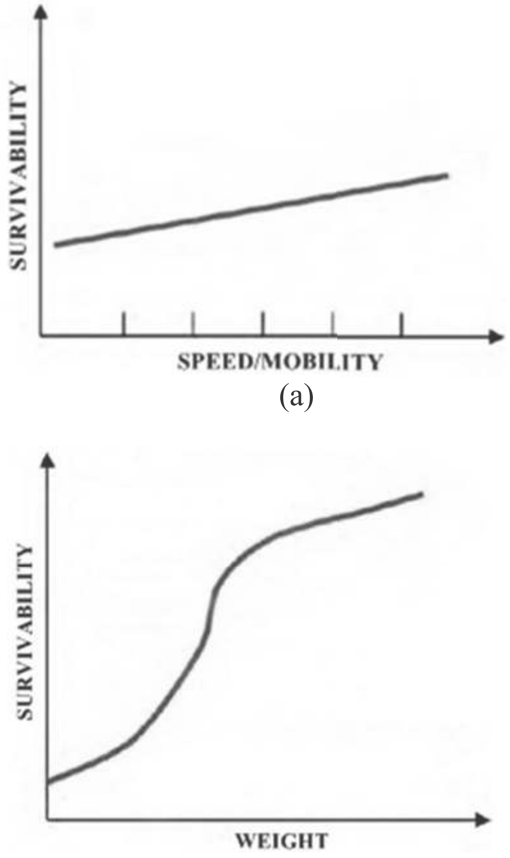
(a) (b)

(c)

Fig 1.9 : (a) Deformed ASB (b) Transformed ASB (c) ASB lading to crack in AA 2024 aluminium alloy (Tiamiyu et al., 2017).

The temperature can reach up to several hundred degrees above the surrounding matrix during the formation of ASBs (Backman, 1969) which is then rapidly cooled by the surrounding bulk material. Formation of ASBs in different metals can be broadly classified as either "transformed" or "deformed" on the basis of their appearance as shown in Fig. 1.9. There is a permanent change in microstructure observed in case of transformed shear bands whereas the deformed shear bands are represented as zones of intense shear deformation of the original microstructure (Backman and Finnegan, 1973). Formation of transformed ASBs is associated with a phase transformation, whereas there is no phase transformation observed in case of deformed ASBs. It has been reported that the stacking fault energy (SFE) of a metallic material also influences the formation of ASBs. Metals with low SFE are more susceptible to the formation of ASBs than that of high SFE metals (Kamijo et al., 1991, Mohammed et al., 2007). ASBs often lead to the formation of cracks in the metal as is displayed in Fig.1.9 (c) and deteriorate the ballistic efficiency of the material (Jena et al., 2010b).

1.7. Aluminium alloys for armour application



(a)

(b)

Fig.1.10: Survivability as a function of: (a) mobility and (b) weight (Madhu and Bhat, 2011).

The armour on combat vehicles has always been constrained by its weight and with rising threat levels this has become an increasingly serious problem. In this scenario, it is worthwhile to consider the competition between the protection and mobility. Enhancing the mobility is essential to improve the manoeuvrability of the vehicle. As has been shown in Fig 1.10 (a), increase in mobility improves the survivability in the battle field (Madhu and Bhat, 2011). However, the increase in mobility leads to a reduction in the weight of the vehicle and often results in a sacrifice in protection (Fig. 1.10 b) (Madhu and Bhat, 2011). Therefore, the relationship between mobility and protection of the armoured vehicle is not a straight forward one. Much effort is consequently being devoted to the development of light weight armour. This provides greater ballistic protection without sacrificing the protection level.

Aluminium alloys have demonstrated considerable promise for armour applications owing to their high strength-to-density ratios. Aluminium alloys are extensively used in applications where weight is an important design criterion. These alloys are very popular in automotive and aerospace applications owing to their high strength, low density, good fracture toughness, good formability, ease of weldability for manufacturing purposes and excellent corrosion resistance. Based on these properties, these alloys are candidate materials for ballistic applications.

Milne-de-Marre graph (Doig, 1998) is often followed to determine an efficient protection to weight ratio, Fig. 1.11. Milne-de-Marre graph illustrates the projectile energy to penetrate a target versus the areal density of that armour material. According to this graph, at plate thickness smaller than 25 mm “steel equivalent” or approximately 70 mm thick aluminium plate, the projectile energy required to penetrate the aluminium plates is higher than those of steels.

A comparative study between the steel and aluminium armour plates was carried out by Budd (1973) is shown in Fig 1.12. It has been shown that the aluminium alloy armour can be superior to steel armour on a weight for weight basis especially against attack by armour piercing rounds and high explosive shell fragments. From previous studies, it is evident that the high-strength aluminium alloys demonstrate equally good or even better resistance to ballistic impact in comparison to steels (Borvik et al. 2010, Forrestal et al.2010). In a previous investigation it has been shown that the aluminium alloys can reduce the weight of a protective structure by approximately 25% in comparison to those of the steels against a similar level of threat (Holmen et al., 2013).

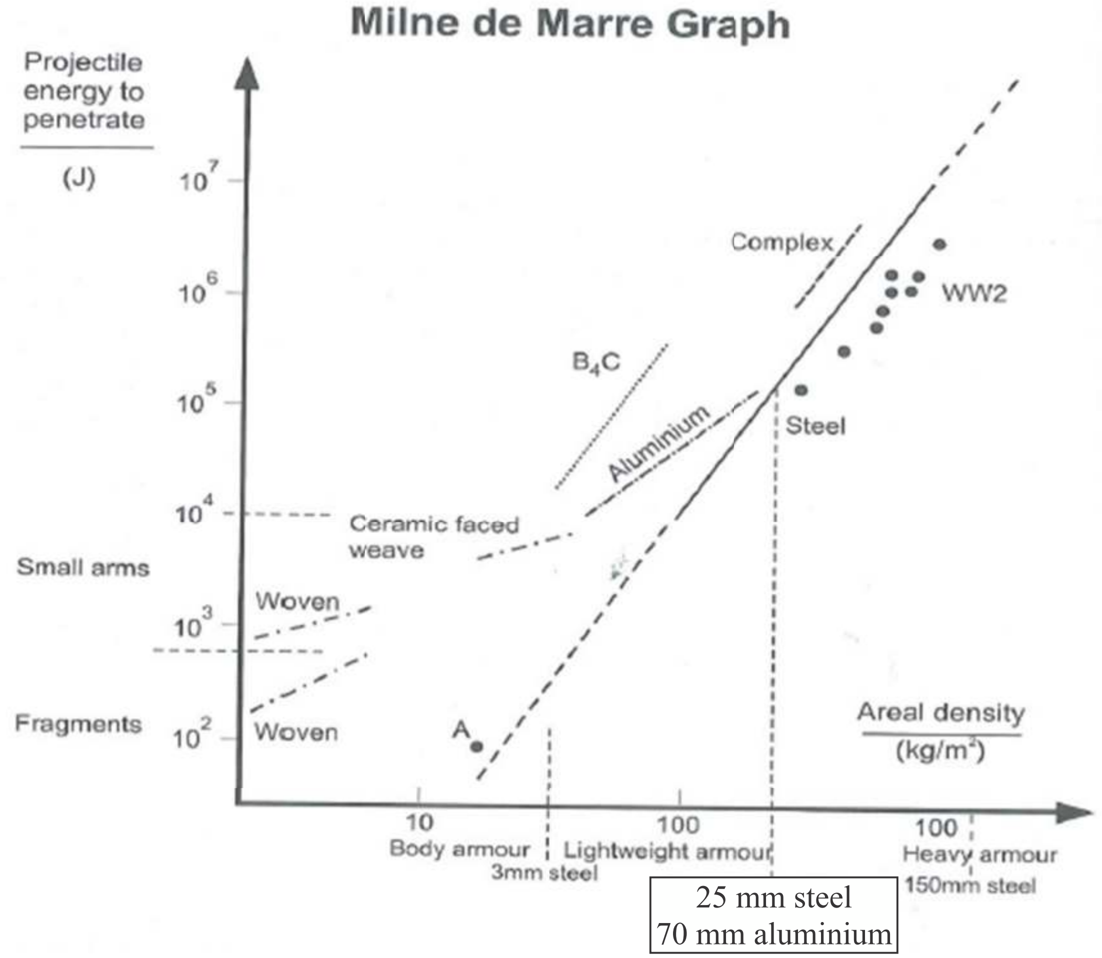
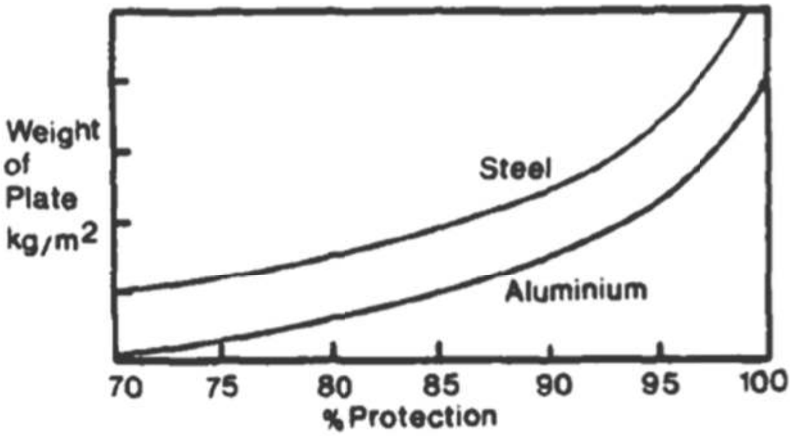


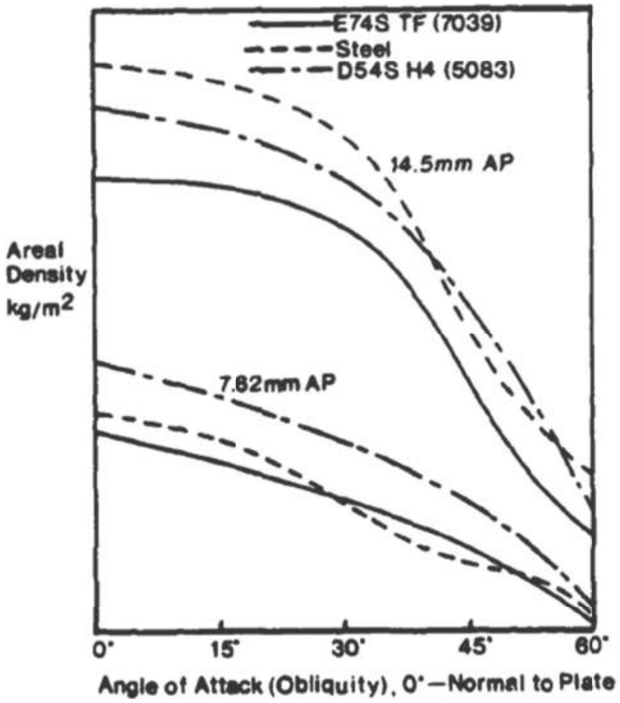
Fig. 1.11. Milne-de-Marre graph (Doig, 1998).

1.8. Brief history of the aluminium alloys used in armour applications

Since the early 1960s, the aluminium alloys have been used for designing armoured military vehicles (Edwards and Crouch, 2016). The first application of aluminium alloys in combat vehicles is seen in US M113 armoured personnel carrier (Fig.1.13 a). The main aluminium alloy used in the fabrication of the shell of M113 is work hardening grade AA 5083. Due to limited strength of work hardening grade aluminium alloys investigations have been made in 1970s to develop heat treatable aluminium alloys with improved strength values. Different series of heat-treatable aluminium alloys were studied and brought out that aluminium-zinc-magnesium base 7000 series aluminium alloys display the best strength values. AA 7039 alloy is used as



(a)



(b)

Fig.1.11: A Comparison between steel and aluminium armour: (a) Protection against 155mm H.E. fragments and (b) Protection against armour piercing rounds(Budd, 1973).

armour in the US Bradley combat vehicles (Fig 1.13 b). In UK, AA 7017 and AA 7020 alloys are used in warrior tracked armoured vehicles (Fig. 1.13 c). The 7000 series aluminium alloys displayed greater ballistic resistance against armour piercing ammunition than that of the work hardening grade 5000 series aluminium alloys. The high strength aluminium alloys suffers from stress corrosion cracking (SCC). For amphibious and naval applications, high resistance to stress corrosion cracking is a pre-requisite criterion. For this reason Al-Cu-Mg base AA 2519 alloy has been developed in the 1990s in US for naval applications. This alloy AA 2519 is used in the critical places of advanced amphibious assault vehicle (AAAV) (Fig. 1.13 d).

(a) (b)

(c) (d)

Fig. 1.13: Image of armoured vehicles with aluminium armour: (a) US M113 (b) US Bradley (c) UK Warrior (d) AAAV combat vehicles.

1.9. Aluminium alloys

Aluminium is a relatively soft, low strength, ductile and malleable metal in its pure form. This limits its use in different engineering applications. Hence significant improvement in its strength is required. This is accomplished either by alloying and/or strain hardening via mechanical deformation. The alloying elements increase the strength of aluminium alloys through solid solution strengthening (interstitial and/or atomic substitution) or through the formation of secondary intermetallic phases by precipitation hardening through tailored heat treatment processes. The desired strength of the aluminium alloys is achieved by a combination of alloying, heat treatment and strain hardening processes such as forging, extrusion and rolling of plate material. The aluminium alloys are designated by four digit numbers where in the first digit indicates the alloy group according to the major alloying element. The second digit reflects modification of the alloy or impurity limits. The last two digits identify aluminium alloy or indicate the alloy purity. The designation of aluminium alloys are given in Table 1.1. Moreover, the aluminium alloys can be grouped into two separate classes in addition to their specific alloy designation: non-heat-treatable and heat-treatable alloys (ASM, 2000). A standardised designation system has been developed to indicate an aluminium alloy's relative mechanical properties and the sequence of treatments applied (Table 1.2)(ASM, 2000).The strain hardened alloys are followed by letter 'H' and the heat treated alloys are followed by letter 'T'.

Table 1.1. Aluminium alloy designation system(Edwards and Crouch, 2016).

Series Number	Major alloying elements	Heat Treatable	Strengthening Method
1xxx	Aluminium purity ≥99.00%	No	Cold work
2xxx	Copper (with magnesium)	Yes	Precipitation - aging
3xxx	Manganese	No	Cold work
4xxx	Silicon	No	Cold work
5xxx	Magnesium	No	Cold work
6xxx	Magnesium and silicon	Yes	Precipitation - aging
7xxx	Zinc (with magnesium)	Yes	Precipitation - aging

1.9.1. Work hardening grades

The heat treatment procedures employed to 3xxx, 4xxx and 5xxx series alloys do not yield any positive influence on their strength properties. The improvement in strength is obtained through work-hardening in these alloys (Van Horn, 1967). Among these alloys AA 5083, AA 5456 and AA 5059 are used for ballistic resistance applications. The requisite mechanical properties of these alloys are achieved through the application of strain-hardening by heavy rolling or extrusion processes.

1.9.2. Age hardening grades

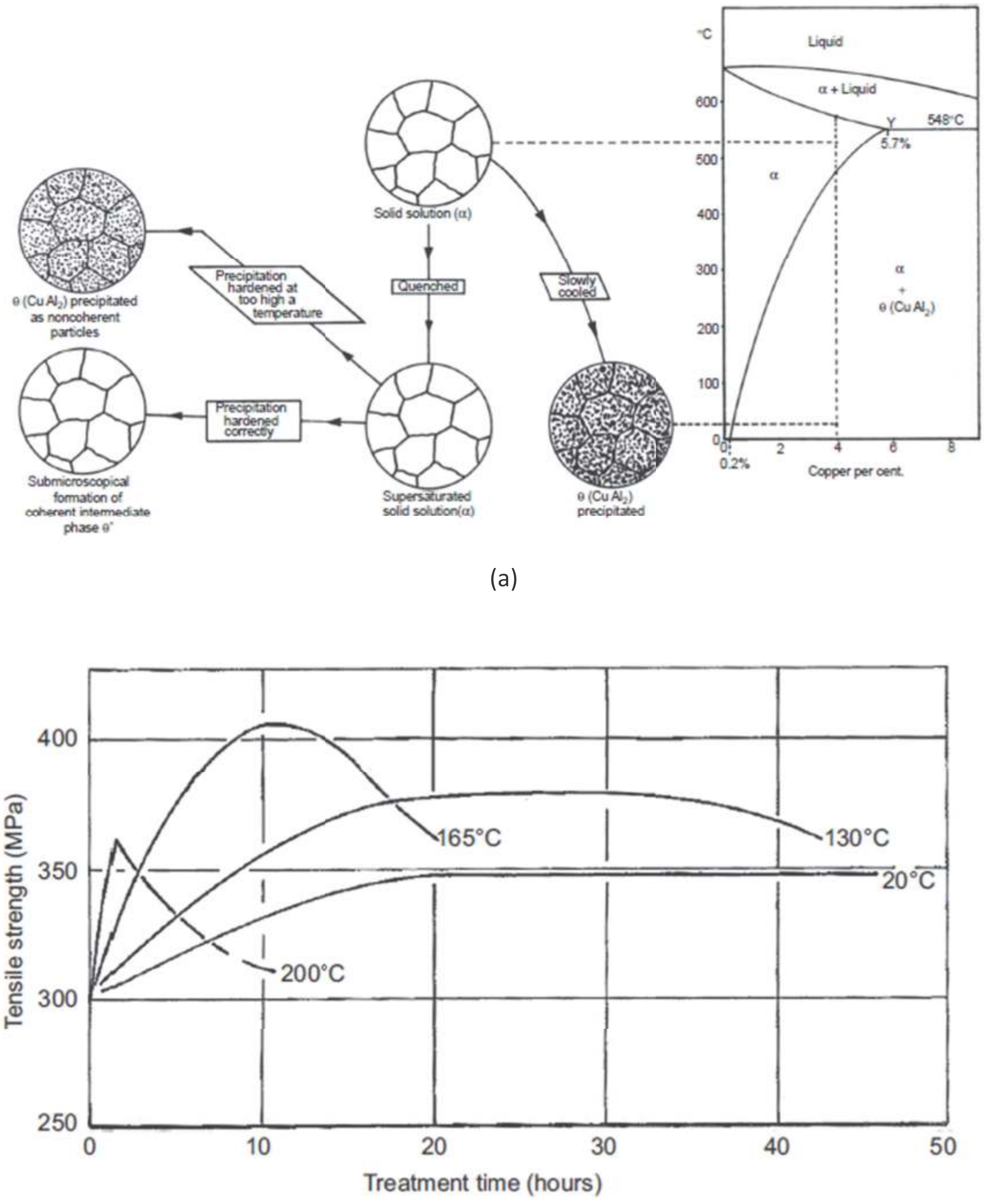
The 2xxx, 6xxx and 7xxx series aluminium alloys are considered as heat-treatable. The major alloying elements in these aluminium alloys are copper, magnesium, silicon and zinc. These alloys form a single-phase solid solution at elevated temperatures. Upon rapid cooling across the solvus line results in a super saturated solid solution. Strengthening occurs through the control heating to an intermediate temperature for a specified period of time. During the aging process, an atomic ordering takes place, which leads to a precipitation and distribution of submicron intermetallic compounds throughout the microstructure (Schlenker, 1970; Van Horn, 1967). The fine-scale precipitates enhance both the strength and hardness of the alloys by affecting the local lattice strain and hindering dislocation movement through the atomic lattice. Maximum strength and hardness is achieved in a microstructure that consists of a high concentration of uniformly distributed precipitates of an optimum size and coherency with the matrix. Long aging times and high aging temperatures stimulate the growth and coarsening of precipitates by over-aging. This brings about an incoherency of the precipitates with the matrix and a decrease in the strength and hardness. A schematic representation of the effect of aging process on the microstructure and tensile properties of a heat-treatable Al-Cu alloy is given in Figs 1. 14 (Higgins, 1968). In heat treatable aluminium alloys, Al-Cu base AA 2219, AA 2519; Al-Mg-Si base AA 6061, AA 6063 and Al-Zn-Mg base AA 7017, AA 7020, AA 7039, AA 7075 alloys have been used as armour materials.

1.10. Ballistic studies on aluminium alloys

For ballistic applications, it is essential to study the extent of penetration by the impact of projectiles and associated damage mechanisms during the impact loading. Several such studies have been carried out on various aluminium alloys. The penetration behaviour of high strength aluminium alloy 7001T6 has shown that it fails in a discing or plugging mode depending on the orientation of the target plate relative to the extrusion direction (Woodward, 1978). From this study it is deduced that the mode of failure is related to stringers of intermetallics parallel to the extrusion direction providing planes of poor fracture toughness in the target plates. The ballistic behaviour of AA 7055 plates during impact of 7.62 mm deformable projectiles in different heat treated tempers has been investigated by Mondal et al (2011). It is demonstrated that ASB induced cracks in the penetration channel decreases the ballistic performance efficiency of the material.

Table 1.2. Summary of temper designations for aluminium alloys(Edwards and Crouch, 2016).

Work-hardened alloys (H)		Heat-treated alloys (T)	
H1	strain-hardened only	T1	T1 cooled from an elevated temperature forming process and naturally aged
H2	strain-hardened and partially annealed	T2	cooled from elevated temperature forming process, cold-worked and naturally aged
H3 treatment	strain-hardened and stabilised by low-temperature heat	T3	solution heat-treated, quenched, cold-worked and naturally aged
H1x, x = 1-9	level of strain hardening and ultimate tensile strength increase	T4	solution heat-treated, quenched and naturally aged
		T5	cooled from an elevated temperature forming process and artificially aged
		T6	solution heat-treated, quenched and artificially aged
		T7	solution heat-treated, quenched and artificially over-aged
		T8	solution heat-treated, quenched, cold-worked and artificially aged
		T9	solution heat-treated, quenched, artificially aged and cold-worked
		T10	cooled from an elevated temperature forming process, cold-worked, and artificially aged



(a)

(b)

Fig 1.14: (a) Schematic of the aluminium rich section of the Al-Cu alloy equilibrium phase diagram illustrating the microstructural relationship of the precipitation hardening heat treatment process; (b) Graphical representation showing the relationship between the precipitation hardening heat treatment time-temperature and tensile strength for an Al-Cu alloy (Higgins 1968).

Ballistic properties of interrupted aged AA 2519A are studied by Gang Gu et al. (2014). It has been observed that the ballistic performance improves with increase in strength of the material. Damage mechanism, deformation and fracture behaviour of AA 2139 has been studied under dynamic condition and the results pointed out towards the importance of microstructure for the better ballistic performance of the material (Chen and Li, 2003). In a study on AA 6061-T6 plates subjected to the impact of steel and tungsten core 7.62 Armour Piercing (AP) projectiles it is noticed that the microstructure modification after ballistic impact is associated with a change in orientation and the creation of ASBs (Manes et al., 2014). This study also pointed out that a large softening takes place adjacent to the impact area when the bullet does not pierce the entire thickness of the target plate than when the projectile perforates through the target plate. Dwilight et al. (2008) have compared the ballistic behaviour of AA 7039, AA 5083 and AA 5059 against armour piercing projectiles and shown that AA 7039 and AA 5059 perform better in ballistic protection than AA 5083. In another study, the ballistic behaviour of Al-Li 2090 alloy, WELDALITE 049 alloy and AA 7039 has been correlated with the formation of ASBs during ballistic impact process (Holmes et al., 1992). It is concluded that formation of a large number of ASBs in AA 7039 alloy has reduced its ballistic efficiency. In the same time, intergranular cracks formed due to coarse grain boundary particles in AA 2090 alloy have prevented the formation of the ASBs and have a beneficial effect on the ballistic performance.

The ballistic properties of AA 6070 aluminium alloy in different tempers are studied by impacting 7.62 mm APM2 bullets against 20 mm thick plates (Holmen et al., 2013). From the ballistic testing, it is detected that the plates with high ductility does not show any fragmentation. In the same time, plates with least ductility show significant fragmentation in the impacted area. It is concluded that despite of fragmentation, strength is a more important feature than ductility for better ballistic performance. Ballistic impact experiments on 6.4 and 7.8 mm thick AA 2219 aluminium alloy sheets using cylindrical steel projectiles at 380-890 m/s velocity have shown that the microstructural damage consists of formation of ASBs at an angle 45° to the rolling plane (Jha et al., 2005). The evolution of microstructure and micro-hardness variation around the crater in AA 2519-T87 aluminium plates oblique impacted by WO-109C type incendiary projectile at a velocity of 816 m/s has been investigated by Xiao-peng et al (2012). A variation in amount of ASB and micro-hardness and a change in size of the precipitates along the penetration channel are reported in this study. It is pointed out that the difference in the micro-hardness of the impact stages is due to work hardening and precipitate coarsening caused by adiabatic temperature rise during ballistic impact.

Perforation of 3.3mm 7A04 aluminium alloy plates at a velocity of 90-170 m/s has been carried out and plugging mode of failure and other structure deformation of the target are studied (Zhang, 2011). Severe fragmentation and delamination of AA7075-T651alloy during impact of blunt and ogive shaped steel projectiles has been illustrated by Pedersen et al. (2011).Impact behavior of AA 7075, AA 5083 and AISI 4140 steel is investigated under 7.62mm armour piercing projectiles by Demir et al. (2008). It has been demonstrated that the AA 7075-T651 displays the best ballistic performance among the tested materials. It is also brought out that AA 7075-T651 provides a 25% reduction in the weight of armour in comparison to RHA steel of 380 HB. Monolithic and layered aluminum 1100H12 targets subjected to oblique impact by ogive nosed projectile is studied by Gupta et al. (2017). It is observed that monolithic targets provide better ballistic resistance than the equivalent thickness layered plates due to higher global deformation experienced by monolithic targets. In a study on the low velocity perforations (in the velocity range 3.5–15.8 m/s) of AA 5083-H116 aluminium plates by cylindrical blunt-nosed projectiles it is observed that plastic anisotropy plays an insignificant role in penetration (Grytten et al., 2009). Perforation experiments on 15-30 mm AA5083-H116 aluminium plates by conical-nose hardened steel projectiles are conducted by Borvik et al. (2004). It has been observed that the perforation resistances of AA 5083 plates are highly competitive to steel and concrete under identical impact conditions.

1.11. Aluminium 7017 alloy

The aluminium-7017 alloy is a Mg–Zn precipitation-hardened alloy and is one of the commonly used armour material in the form of rolled plates. This alloy has been successfully used as armour on British and German armoured ground systems (Hazell, 2015). The black regions in the Fig. 1.15 shows the AA 7017 plates placed in the hull portion of the UK made Warrior tracked vehicles. The chemical composition and some physical properties of AA7017 alloy is shown in Tables 1.3.

1.12. Studies on AA 7017 aluminium alloys

Previous studies have focused mainly on the high strain rate behavior of AA 7017 aluminium alloy under different strain rates and temperatures and to develop model for 7017 aluminium alloy (Bobbili et al., 2015). It has been shown that there is an improvement in dynamic strength of AA 7017 alloy with increase in the strain rate and the mode of fracture changes from shear at lower strain rates to ductile at higher strain rates. Influence of aging treatment on stress corrosion cracking behaviour of AA 7017 alloy has been studied extensively by Rout et al. (2015) Results reveal that AA 7017 alloy tempers are not susceptible to stress corrosion cracking in 3.5 wt.% NaCl solution at free corrosion potential. However, severe damaging to stress corrosion cracking is observed at applied anodic potentials due to non-recrystallized grain structure and the presence of discrete, widely spaced, not-interconnected precipitates at the grain boundaries.

The shock induced mechanical properties of the AA 7017 as a function of heat treatment has been investigated by Millet et al. (2004). It is depicted that while tensile and spall strength of peak aged and under aged material are identical the Hugoniot elastic limit of peak aged material is higher than the under aged material. In a previous study an adiabatic plugging mode of failure has been reported in AA 7017 plates impacted with deformable projectiles (Jena et al., 2010c). It is observed that the propagation of shear bands have occurred at the target projectile interface leading to cracking and an ASB induced shear plugging. In another study on the oblique impact of AA 7017 plates with armour piercing projectile it is observed that the propagation of shear bands occurred at the target projectile interface leading to cracking up to 30° angle of attack (Jena et al., 2010b). The mode of failure changes to gouging and the intensity of the adiabatic mode of failure decreases with increase in angle of attack beyond 30°. A comparison of high strain rate flow behavior of 7055 and 7017 aluminum alloys using various test methods such as Dynamic Indentation (DI), Taylor Impact, and Split Hopkinson Pressure Bar (SHPB) have been reported by Mishra et al (2014). From this study it is shown that no single test method could reflect the actual ballistic penetration behavior individually.

Fig. 1.15: The exposed hull of Warrior tracked vehicle showing the use of AA 7017 plates in its hull portion (Hazell, 2015).

Table 1.3. AA-7017 plate chemical composition and properties at room temperature (Jena et al., 2010b).

Composition (Wt%)	5.2 Zn, 2.3 Mg, 0.35 Si, 0.35 Cr, 0.45 Fe, 0.2 Mn, 0.1 Zr, balance Al
Crystal structure	FCC
Density (g/cm^3)	2.78
Melting temperature (˚C)	638
Elastic Modulus (GPa)	75
Poisson's ratio	0.3

1.13. Scope of the present work

Materials for ballistic applications are generally used in the form of thick rolled plates which are produced by a combination of different thermo-mechanical processes e.g. forging, rolling and subsequent heat-treatments. This introduces preferred direction of grains i.e. crystallographic texture in the materials. As a result, these materials exhibit mechanical property anisotropy. It has been reported that plates of aluminium alloy display anisotropy in mechanical properties due to crystallographic texture developed during the thermo-mechanical processing (Barlat et al., 1991; Seidt and Gilat, 2013; Chen et al., 2009). A thick plate has three principal directions namely longitudinal (L), Long transverse (LT) and short transverse (ST)(Fig. 1.16). The plate displays different microstructures in terms of grain size and aspect ratio of grains along the three directions. This results in different mechanical properties. In an earlier study, Lee and Liu (2014) have shown from the Split-Hopkinson pressure bar (SHPB) experiments that the impact properties of 6061-T6 aluminium alloy are strongly dependent on the direction of the grains. It has been observed that the AA 6061 aluminium alloy in T6 condition exhibits maximum strength in samples parallel to transverse direction at strain rates ranging from 1×10^3 to 5×10^3 s^{-1}. In another study on the quasi-static tensile behaviour of AA 2024 aluminium alloy it is observed that yield strength and elongation are higher in longitudinal and transverse direction than the through thickness direction (Khan, 2013). Vignjevic et al.(2002) have established from the plate impact experiments that the longitudinal direction is stronger than the short transverse direction in AA 7010-T6 aluminium alloy. However, investigation of the ballistic behaviour of a material in three directions of a rolled plate product wherein microstructural variations are quite large is somewhat limited.

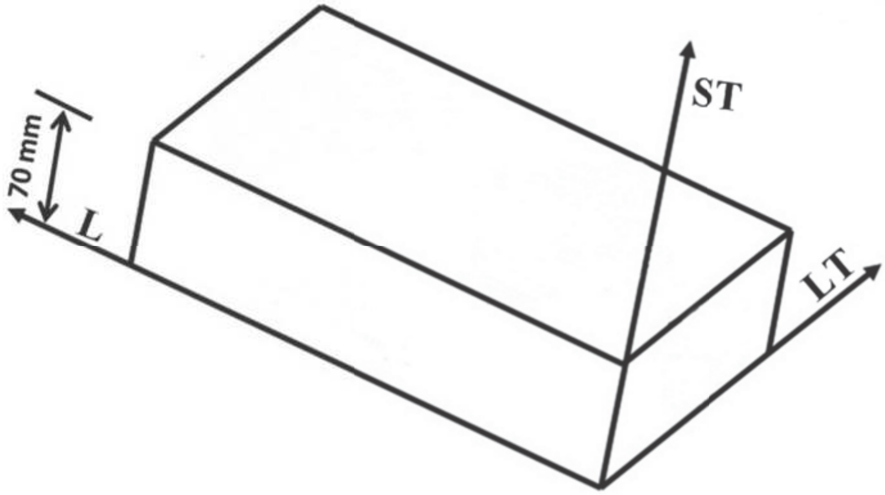


Fig. 1.16: Schematic representation of the three principal directions in the AA-7017 plate.

Thermo-mechanical processing leads to two types of anisotropy namely, in-plane and through-thickness in rolled products (Mehta et al., 2014). The thin sheet products typically display in-plane anisotropy i.e. variation in mechanical properties in different sample directions. Thick plate products, on the other hand have through-thickness anisotropy exhibiting different mechanical properties from centre to surface of the plate. Consequently, these variations must be taken into account while designing and making components for ballistic application. As a result of through-thickness anisotropy, hot rolled and peak aged AA 7017 alloy plates display different microstructures and associated grain orientations across the thickness of the plate. This in turn exhibits different mechanical and ballistic properties. It is therefore essential to understand the effect of through thickness anisotropy on the ballistic behaviour of a thick plate.

There have been a number of investigations aimed at correlating ballistic performance with mechanical properties. Majority of the earlier investigations have demonstrated the strong dependence of ballistic properties on the strength and hardness of the target material (Dikshit et al.,1995, Übeyli et al., 2007). Some other studies have correlated the ballistic impact resistance with ductility and Charpy impact toughness of the material (Dey et al.,2004, Pereira and Lerch, 2001). In another study it is observed that optimum ballistic performance can be achieved by a combined effect of all the mechanical properties (Jena et al. 2010a). Heat treatment is one of the thermo-mechanical processes which can be employed effectively to optimize mechanical properties for best ballistic performance.

The present work focuses on understanding the ballistic behaviour of a 70 mm thick AA 7017 plate in L, LT and ST directions. Investigations have also been carried out to find out the effect of through thickness anisotropy on the ballistic behaviour of the 70 mm thick AA 7017 alloy plate by impacting on its surface and centre. An attempt has been made to correlate the ballistic behaviour of the material with corresponding microstructure, texture and static mechanical properties along L, LT and ST directions as well as at centre and surface of the plate. The ballistic behaviour of AA 7017 alloy has been further investigated in different heat-treated conditions against hard steel and lead projectiles. Finally, the ballistic behaviour of AA 7017 alloy has been compared with five other commercially available aluminium alloys namely AA 2024, AA 2519, AA 5059, AA5083 and AA 6061 used for armour application.