2. Experimental Details

2.1. Introduction

This chapter provides a brief description of the materials used for the present study and experimental techniques adopted for heat treatment, microstructural characterization, texture measurement, mechanicaland ballistic property evaluation.

2.2. Material

The aim of this thesis is to study the ballistic behaviour of AA 7017 aluminium alloy against small calibre ammunitions. This investigation intends to establish microstructure-texture-mechanical property-ballistic property correlation in AA 7017 alloy platesand compare the ballistic behaviour of AA 7017 with AA 2024, AA 2519, AA 5059, AA 5083, AA 6061 aluminium alloys. For this investigation,AA 7017 aluminium alloy plates were obtained from Alcan International (U.K.),whereas the other aluminium alloys e.g. AA 2024, AA 2519, AA 5059, AA 5083, AA 6061 were acquired from Aleris International (USA). The aluminium alloys were received in the form of rolled plates. The initial dimension andthe as received condition of the different aluminium alloy plates are displayed in Table 2.1.The analysed chemical compositions of the different alloys are given in Table 2.2.

The as received material was used to understand the effect of through thickness anisotropy and grain orientation on microstructure, texture, mechanical and ballistic property of AA 7017 alloy. The as received materials were also used for comparison of the ballistic performance of different aluminium alloys. Subsequently, the AA 7017 alloy is subjected to

different heat treatment conditions in order to evaluate the effect of aging on the mechanical and ballistic behaviour.

Table 2.1: Initial plate dimension and as received condition of studied aluminium alloy plates

Al alloy	Plate dimension (mm)	Plate thickness (mm)	Plate as received condition
AA 2024	2000 × 1200	20, 70	T6
AA 2519	2000 × 1200	20	T6
AA 5059	2000 × 1200	20	H3
AA 5083	2000 × 1200	20	H3
AA 6061	2000 × 1200	20, 70	T6
AA 7017	2000 × 1200	20, 70	T6

Table 2.2: Chemical composition of the different aluminium alloys

Material	Cu	Mg	Si	Mn	Fe	Ti	Cr	Zn	Al
AA 2024	4.05	1.43	0.43	0.38	0.32	0.017	0.1	--	Balance
AA 2519	5.5	0.3	0.23	0.4	0.3	--		0.1	Balance
AA 5059	0.2	5.6	0.3	1.0	0.4	0.2	0.2	0.6	Balance
AA5083	0.1	4.7	0.4	0.7	0.3	0.15	0.2	0.23	Balance
AA 6061	0.4	1.2	0.8	0.15	0.7	0.15	0.35	0.25	Balance
AA 7017	--	2.3	0.35	0.2	0.45	--	0.35	5.2	Balance

2.3. Heat treatment

For heat treatment studies, the 70 mm plates were hot rolled to 40 mm thickness. The samples were solution treated (ST) at 470 °C for 1.5 hours, quenched in cold water, followed by artificial aging. The samples were aged at three different ageing conditions namely under-

aged (UA), peak-aged (PA) and over-aged (OA). The ageing parameters are given in Table 2.3. These are taken from previous heat treatment study on AA 7017 alloy (Rout and Ghosh, 2012).

Table 2.3. Aging schedule for differently heat treated AA-7017 alloy

Material	Aging Condition	Heat treatment parameters	Cooling
AA 7017	Under-aged	1h at 130°C	Air Cooling
	Peak-aged	24h at 130°C	Air Cooling
	Over-aged	100h at 130°C	Air Cooling

2.4. Differential scanning calorimetry (DSC)

In order to understand the precipitation sequence of the AA-7017 alloy, differential scanning calorimetry (DSC) study was carried out. DSC experiments were conducted from ambient temperature to 520° C at a heating rate of 20 °C/min in nitrogen atmosphere, using a NETZSCH instrument (204FI Phoenix model). Alumina was used as a reference material. The net heat flow to the reference material was recorded as a function of temperature.

2.5. Characterization

2.5.1. Metallography

2.5.1.1. Optical microscopy (OM)

Metallography examinations of all the studied aluminium alloy plates were carried out following standard metallographic procedures used for aluminium alloys. For the as received AA 7017 alloy plates metallographic observations were made in three sample directions namely L, LT and ST directions as well as in the surface and centre of the plates. Microstuctural studies were also conducted on AA 7017 samples in the heat treated condition.

Metallographic samples were prepared using conventional grinding and polishing. The cut specimens were mounted in bakelite mount and polished initially with belt grinder to remove outer rough surface or coating materials. Different grades namely, 80, 120, 220, 320, 400, 600, 800, 1000 and 1200 grit polishing SiC papers were used for mechanical polishing. Consequently, the mechanical polished samples were subjected to velvet cloth polishing with different grades of diamond paste (9 μm (coarse cloth polishing), 3 μm (medium cloth polishing) and 1/2 μm (fine cloth polishing)). The samples were kept in acetone and cleaned by ultrasonically for 5 min. The ultrasonic cleaning was repeated two to three times for each specimen. The polished samples were etched with Keller's reagent (5mL HNO_3, 3mLHCl, 2mL HF and 190 mL water). The etched materials were examined in optical microscope (Leica Microsystems CMS GmbH).

2.5.1.2. Scanning electron microscopy (SEM)

The samples for scanning electron microscopy were prepared using the above metallographic techniques. The samples were examined in SEM (Leo 440) in back scattered electron (BSE) and secondary electron (SE) modeswith out etching. The tensile and impact fracture surfaces were also examined in SEM to find out the fracture morphology. .

2.5.1.3. Electron probe micro analyser (EPMA)

EPMA analysis was made in the AA 7017 alloy to get the chemical composition of the precipitates and matrix phase present in the as received condition. The samples for EPMA (CAMACA SX100) were prepared using the standard metallographic techniques.

2.5.2. X-ray diffraction (XRD)

The AA 7017 alloy is subjected to X-ray diffraction (XRD) studies in a Philips PW3020 diffractometer coupled with graphite monochrometer. The samples are irradiated with CuKα radiation obtained from a copper source operated at 40kV and 25mA. These were investigated in step scan mode. The experiment parameters of step scan mode are given in Table 2.4. XRD studies were carried out on the as received as well as heat treated AA 7017 samples.

Table 2.4. Experimental parameters used for X-Ray diffraction measurements.

Radiation	CuKα
Scan mode	Step
Start angle	29°
End angle	90°
Step size	0.02°
Time per step	2.7 sec

2.5.3 Texture measurement

The texture measurements for the as received 70mm AA 7017 plates (25×15 mm^2 in size) were carried out at three different sample directions, namely L, LT and ST directions as shown in Fig 2.1 and also from the 1/2 and 1/8 thickness levels from the surfaces. The texture measurements of heat treated plates were carried out at the 1/8 thickness levels from the surfaces. An Inel G3000 texture goniometer coupled with curved position sensitive detector (PSD) using CuKα radiation was employed for texture measurements in Schultz back reflection technique (Schultz, 1949). Three incomplete pole figures {110}, {200} and {211} were measured using an oscillation stage employed with 20 mm specimen translation to increase the measured area. These pole figures were corrected for defocusing and absorption using powder samples of the corresponding alloys. From the pole figures, thecomplete Orientation Distribution Function (ODF) plots were obtained using Arbitrarily Defined Cells (ADC) algorithm with the ghost correction. The Labotex 3.0 software was used for ODF calculation. These results are presented in Bunge notation as ODF plots of constant φ_2 sections with iso-intensity contours in the Euler space defined by three Euler angles (φ_1, Φ, φ_2) and typical β fibre (Bunge, 1982). The experimental parameters are given in Table 2.5.

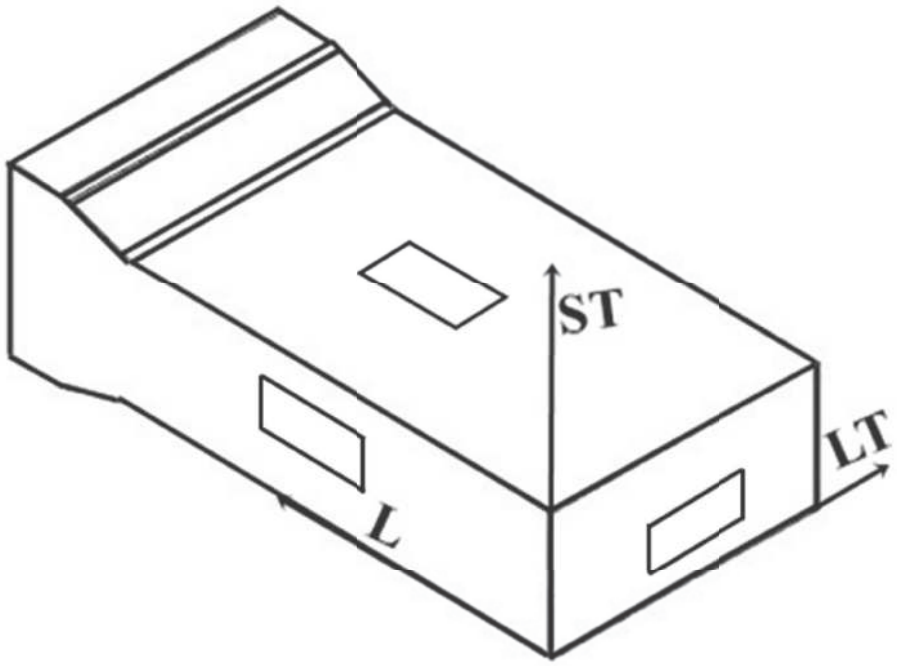


Fig.2.1: Schematic of the texture measurement samples taken from three directions.

Table 2.5: Experimental parameters used for Texture measurements.

Voltage	**40 kV**
Current	**30 mA**
ψ	**0 – 75 with 5° step**
χ	**0 – 360 with 5° step**
Scan time / step	**10 Sec**
Oscillation	**± 20 mm**

2.6. Mechanical property evaluation

2.6.1. Hardness measurements

Bulk hardness values in terms of Vickers Hardness Number (VHN) of the Aluminium alloys were measured according to ASTM E 140-02 using AFFRI hardness tester (model: VRSD 270). Bulk hardness values of AA 7017 alloy is measured in the as received as well as in the heat treated conditions. 5 kg load was used to determine the hardness of the Aluminium samples. Ten measurements for each specimen were carried out in the hardness tests and the average values are reported. After ballistic evaluation of the plates, Vickers micro hardness was obtained adjacent to the crater wall along the path of the projectile from entrance to exit using a Matsuzawa Co. Ltd. hardness tester (model: A MMT-X7) at 100g load.

2.6.2. Tensile tests

For evaluation of tensile properties of the as received AA 7017 alloy plate along three different sample directions as well as from surface and centre of the plate, tensile samples were machined as shown schematically in Fig 2.2. Tensile properties were also evaluated for AA 7017 alloy in different aging condition. In case of the AA 2024, AA 2519, AA 5059, AA 5083, AA6061 tensile properties were evaluated along the rolling direction of the plates. The schematic diagram of the tensile specimens is given in Fig. 2.3. The size and geometry of the specimens as well as the testing procedure are in accordance with ASTM E8-2009. The specimens were tested under tension at a strain rate of $4.8\times10^{-1}s^{-1}$ using an Instron 5500R Universal Testing machine (Instron Corporation, Norwood, MA). An axial type extensometer (model 1267: Instron U.K.) was used for strains measurement with a specified gauge length of 10 mm. Five samples were tested for each study and theaverage values of yield strength (σ_{YS}), ultimate tensile strength (σ_{UTS}) and elongation are reported.

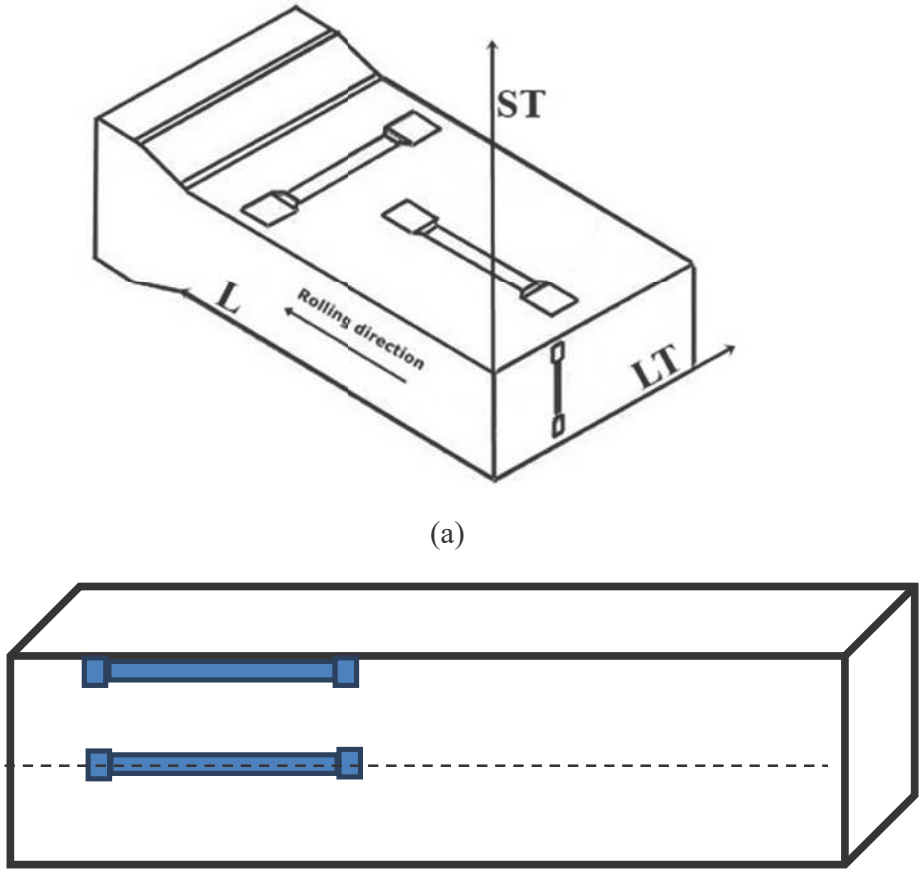


Fig. 2.2: Schematic of tensile sample preparation in as received AA 7017 plates; (a) along L, LT and ST direction, (b) from surface and centre.

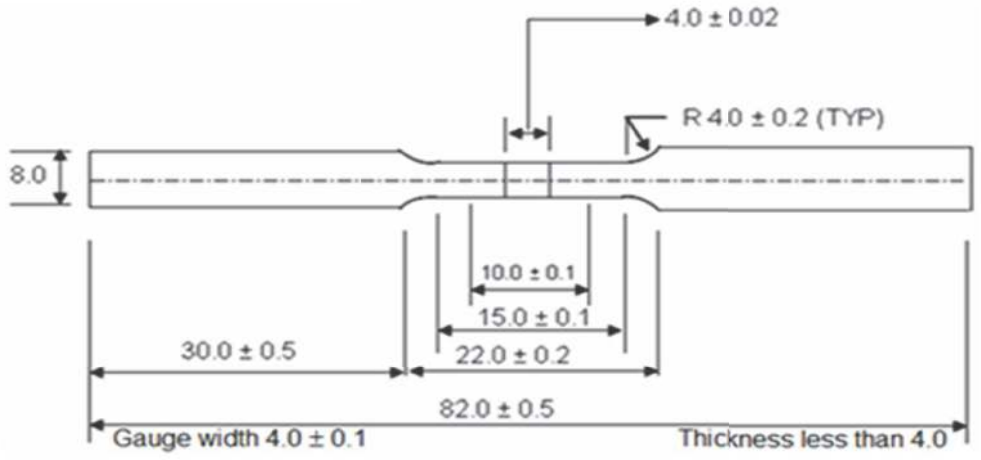
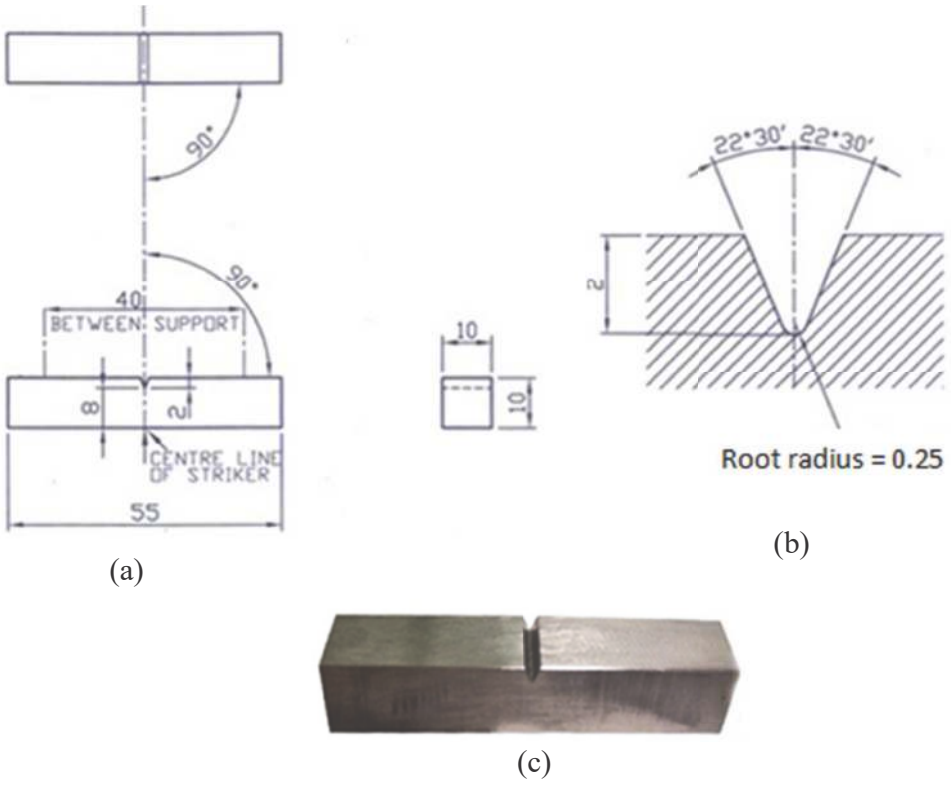


Fig. 2.3: A schematic diagram of tensile specimen (dimensions are in mm)(ASTM E8-2009).

2.6.3. Impact tests

Impact samples were machined for all the studied aluminium alloys. Similar to tensile samples, Charpy impact samples were machined along three different directions as well as from the surface and centre of the as received AA 7017 plate. Impact properties were also evaluated for the AA 7017 plates in the heat treated condition. Standard Charpy V-notch (CVN) specimens (10×10×55 mm size) with 45° angle were made as per the ASTM standards (E23-02a) and the tests were carried out at room temperature to find out the impact properties. The weight of the test hammer employed for testing was 18.7 kg and the angle of hammer before striking was 90° to the test specimen. The schematic diagram of the Charpy impact specimens is given in Fig. 2.5. Five samples were tested for each study and their average value was taken as the impact value of plate.



(a) (b)

(c)

Fig. 2.4: (a) A schematic diagram of impact specimen (dimensions are in mm), (b) Enlarged view of notch for test piece (c) A Charpy impact sample before testing(ASTM E23-02a).

2.7. Sample preparation for ballistic testing

The surface of the target plate can affect the ballistic performance of the material. Cracks present in the surface can deteriorate the ballistic impact resistance of the material. Hence, it is essential to prepare the samples for ballistic testing with a precise cutting. A water jet cutting machine (OMAX 55100) was employed for cutting of the ballistic testing samples. Care was taken in order to obtain a smooth cutting surface.

To correlate the through thickness anisotropy of the AA 7017 plate with ballistic performance, samples of 150 mm x 150 mm x 70 mm size were cut from a big plate. The plates were subsequently sliced at the mid thickness as shown in Fig. 2.5. Out of these sliced samples five samples were impacted with the top surface of the starting plate (surface) facing the projectile. Five other samples were impacted with the centre plane of the starting plate (centre) facing the projectile.

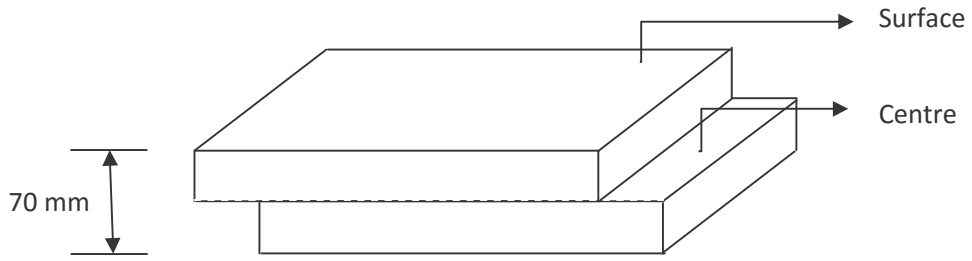


Fig.2.5: Schematic representation of the sectioning of the 70 mm thick AA 7017 plate. The plates were sliced along the dotted lines in the centre into two halves.

In order to establish relationship between the ballistic behaviour and orientation of the material with respect to rolling direction, plates of 200 × 70 × 70 mm size were cut from a single plate (Fig.2.6). It was ensured to keep the dimension of the ballistic testing samples equivalent in order to avoid any effect on the ballistic performance due to difference in the plate size. A 70 mm wide block was cut in the rolling direction of the parent plate. From this block, 200 mm length samples were cut. The final dimension of the ballistic testing samples was thus 200×70×70 mm. As can be seen from Fig 2.6, these samples have a cross section of

200×70 mm parallel to L direction of the parent plate in one of its sides and a cross section of 200×70 mm parallel to ST direction of the parent plate in its other side. Similarly 70 mm wide blocks were cut transverse to the rolling direction of the parent plate to get a cross section of 200×70mm parallel to LT direction of the parent plate. In this manner samples of 200×70×70 mm were prepared for ballistic experiments with at least one of the sides with a dimension of 200×70mm parallel to a principal direction of the parent plate. Ballistic evaluation is conducted by impacting projectiles on these faces.

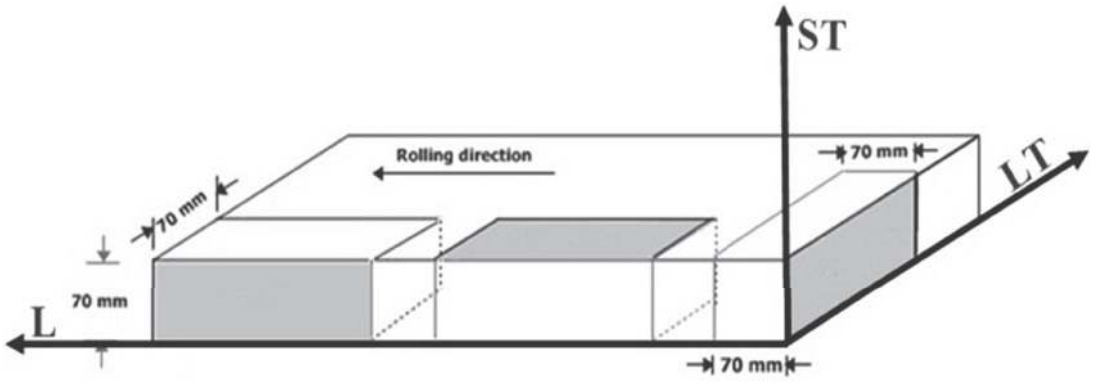


Fig 2.6: Schematic of ballistic testing sample preparation to establish correlation between ballistic behaviour of the material with grain orientation.

Samples of 150 ×150 × 40 mm and 150 × 150 × 25 mm were prepared from the heat treated AA 7017 plates and were tested against high hardness steel and lead projectiles, respectively. In order to compare the ballistic performance of the studied aluminium alloy plates, samples of 150 × 150 × 20 mm size were prepared and tested with lead projectiles. Ballistic samples of 200 × 200 × 70 mm were machined for AA 2024, AA 6061 and AA 7017 plates and tested against high hardness steel projectiles.

2.8. Ballistic testing

Ballistic experiments were conducted in a small arms range employing a standard rifle. The ballistic testing arrangement is displayed in Fig. 2.7. The small arms range

consisted of a firing chamber, a long tunnel and an observation chamber. The gun was mounted on a rigid stand. The target plate was held onto the fixture with C-clamps which was located in the tunnel at a distance of 10 m from the gun.The ballistic evaluation of the target plates was carried out at 0° angle of attack. Two different caliber projectiles namely 7.62 mm and 12.7 mm were used for ballistic evaluation studies and are shown in Fig 2.8. The different properties of the projectiles used for ballistic testing are given in Table 2.6. The impact and residual velocities of the projectile were measured with the help of four aluminium velocity foil screens by measuring the time interval between the interceptions caused by the projectile running across the Aluminium foils kept a fixed distance apart. The first two screens were placed at 6 m and 8 m distance from the muzzle of the gun in order to measure the striking velocity. The other two Aluminium foils were placed 0.2 and 0.4 m behind the target to determine the residual velocity of the projectiles. The striking velocities of the projectiles were measured as 840 ± 15 m/s. By proper laying of the gun, it was ensured that the centre-to-centre distance between any two impact craters on the plate was at least three times the diameter of the projectileto ensure that the zones of plastic deformation formed around the crater were not influenced by the earlier ones. Each target plate was subjected to at least three shots and three sets of plates were ballistically impactedfor every study in order to get the ballistic behaviour statistically. Kinetic energy absorbed by the target plate was determined by using the striking and residual velocities of the projectiles. Energy absorption was calculated from the difference in kinetic energies of the projectile before impact and after perforation as given by the following formula.

$$E_{abs} = \tfrac{1}{2} MV_s^2 - \tfrac{1}{2} MV_r^2 \qquad (2.1)$$

Where Eabs = Energy absorbed by the projectile, M = Mass of the projectile, Vs =Striking velocity of the projectile, Vr = Residual velocity of the projectile. For thicker plates, depth of penetration (DOP) method was used to evaluate and compare the ballistic performance of target plates (Jena et al., 2010).Fig. 2.8 shows the schematic of the depth of penetration measurement. In this method, a fine needle of 0.75 mm diameter with a pointed tip was inserted into the crater after ballistic impact. Care is taken to touch the bottom most portion of the crater. The portion of the needle remain above the plate is measured minutely with the

help of a verniercalipers. Then deducting it from the total needle length the actual depth of penetration was obtained. The average DOP values are measured and are reported.

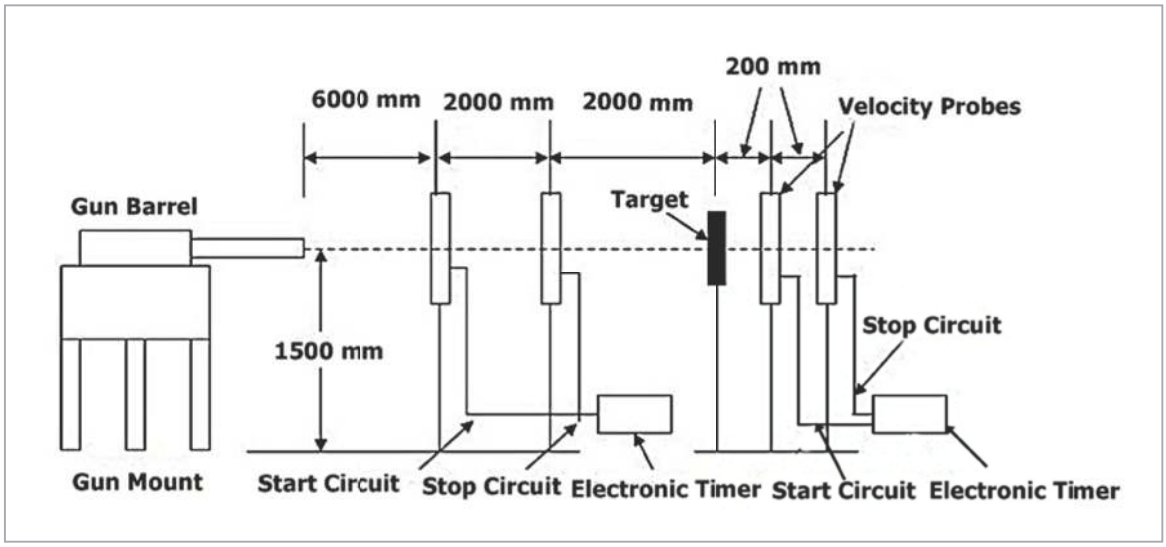


Fig 2.7: Schematic of ballistic testing set up (Jena et al. 2010a).

Fig 2.8: Different calibre projectiles used for ballistic experiments (Jena et al., 2016).

Table 2.6.Some properties of the projectiles.

Parameters	7.62 Ball	7.62 AP	12.7 AP
Cartridge Length	70.88±0.48 mm	70.88±0.48 mm	147.3±0.2 mm
Cartridge material	Copper	Copper	Copper
Jacket material	Brass	Soft steel	Soft steel
Core material	Lead	High hardness steel	High hardness steel
Hardness of core material	25 VHN	700 VHN	700 VHN
Bullet length	26.53 mm	26.53 mm	52.7 mm
Diameter of the projectile	5.66 mm	6.06 mm	10.75 mm
Nose type	Conical	Conical	Conical
Core weight	5.342	5.342	30.049
Jacket weight	4.849	4.849	17.813
Total bullet wt (core weight + jacket wt)	10.375	10.375	48.424
Bullet weight with brass jacket	9.034 gram	22.781	129.47
Striking velocity	840±10 m/s	840±10 m/s	840±10m/s
Kinetic energy	1.885 kJ	1.885 kJ	10.6 kJ

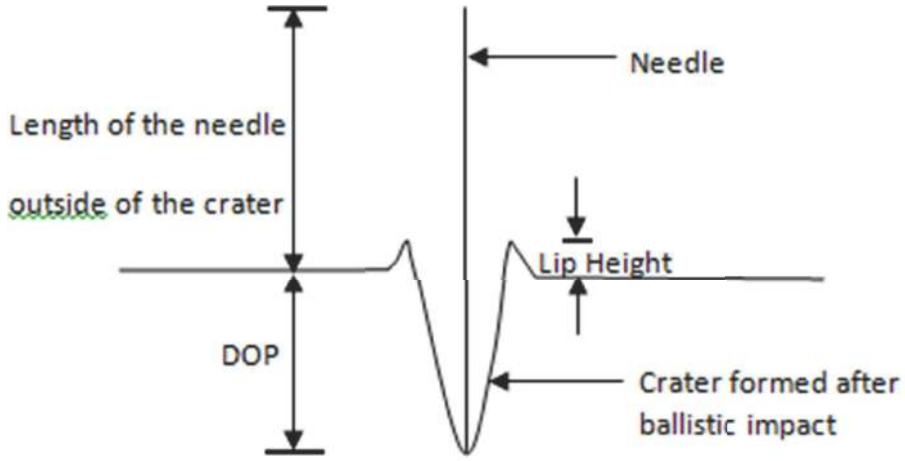


Fig 2.9: Schematic of DOP measurement method (Jena et al., 2010)