Full Paper

MECHANICAL AND BALLISTIC CHARACTERIZATION OF ARMOUR STEEL PLATE AGAINST 0.30-CALIBRE APM2 ARMOUR PIERCING PROJECTILE

O. M. Sanusi
Research and Development Centre,
Defence Industries Corporation of Nigeria, Kaduna.
Department of Mechanical Engineering,
Federal University Oye-Ekiti,
Ekiti, Nigeria.
sanuthwale@gmail.com

J. O. Akindapo
Department of Mechanical Engineering,
Nigerian Defence Academy, Kaduna, Nigeria.

M. Dauda
Department of Mechanical Engineering,
Ahmadu Bello University,
Zaria, Nigeria.

Y. Bello
Department of Mechanical Engineering,
Nigerian Defence Academy,
Kaduna, Nigeria

M. O. Olaleke
Research and Development Centre,
Defence Industries Corporation of Nigeria,
Kaduna, Nigeria.

ABSTRACT

An experimental analysis of SAN-armour steel plate subjected to high velocity impact of 0.30 calibre armour piercing projectiles is presented. The hardness and impact strength of the plate were assessed following standard procedures; while microstructural examination was carried out on etched sample of the plate. The ballistic performance of the 6 mm thick steel was examined, to obtain an estimate for the V_{50} ballistic test for armour steel plate, impacting projectiles at 30° obliquity to the target plate from 20 m range. The observed performance was compared with the requirements ofMIL-STD-46100E standards. The results showed that the specimen tested has a tensile strength of 1290MPa, hardness value of 483HBN, 10.1% elongation, impact resistance value of 27J, and that the morphology of the original microstructure has martensitic/bainitic matrix. The ballistic performance of the plate agreed with the minimum ballistic requirements of MIL-STD-46100E standards. This study, therefore established that the SAN-armour steel plate is effective for anti-ballistic applications.

Keywords: *V_{50}, ballistic, 0.30 calibre, armour, defence, austenisation, quenching*

1. INTRODUCTION

Contemporary protective materials play important roles in providing barriers to modern firearms/ projectiles. Thus, studies on the search and development of protective materials such as steels, ceramics and composite materials have gained importance (Atapek and Karagoz, 2011). Atapek (2012) said that selecting appropriate material, processing conditions, and final microstructural and mechanical properties immensely affect the protective characteristics of materials under any dynamic loading.

Metals are still the most widely used materials in armour design. The main advantage of metals over other materials is that, they are capable of carrying structural and fatigue loads while offering efficient protection. They are less expensive compared to the other materials (Deniz, 2010). Deniz (2010) explained that the most commonly used metallic material in armoured fighting vehicles is steel. The main properties such as toughness, hardness, good fatigue strength, ease of fabrication and joining and relative low cost make it a popular material for armoured vehicle hulls.

Defence industries all over the world are presently undergoing research efforts in delivering light-weight armour technologies that result in optimized performance against battlefield threats, including Armour Piercing (AP) projectiles (Dwight, 2011; William, 2009). Such protection has to be provided at realistic areal densities at affordable prices. Few countries produce a wide range of quenched and tempered steel grades of varied hardness and toughness which are very lean in alloy content and are beginning to be used in a number of armour applications. Quenched and tempered steel is still quite competitive as an armour material for many ballistic applications (Atapek, 2012) and is the subject of the present study.

Two of the most common armour steel grades in use are MIL-A-12560H Class 1 Rolled Homogenous Armour (RHA) with a hardness range of 241– 388HB (US Military Specification, 2000) and MIL-A-46100D High Hardness Armour (HHA) with a hardness range of 477-534HB (US Military Specification, 1988). Both specifications had their origins in World War II and had not changed remarkably. The former has been modified recently (September 2000) to become more of a unified specification, incorporating a new class of wrought armour plate (Dwight, 2007), Class 4, which is heat treatable to higher hardness ranges than Class 1. This new class is divided into two sub-classes, defined by whether the armour plate is for a structural or non-structural application (Dwight, 2007).

Various researches confirmed that ballistic performance increases with steel hardness and toughness (Maweja and Stumpf,

Table 1: Armour Classes

Armour Class According to DEF(AUST) 8030	Hardness Equivalences (HB)			
	DEF (AUST) 8030[1]	U.S. Military Specification Approx. Nominal Equivalent Grade	DEF STAN 95-24 Approx. Nominal Equivalent Grade	Bisalloy Steels Grades
Class 1	Not Explicitly Specified	No Equivalent	No Equivalent	Bisplate 80A (235-293)
Class 2	2A: 260-310 2B: 280-330	MIL-A-12560H Class 2 <31.8 mm (277-321)	Class 1 (262-311)	Bisplate High Impact Armour (HIA) Class 2 (277-321)
Class 3	340-390	MIL-A-12560H Class 1 <12.7 mm (341-388) 12.7 to <19.1 mm (331-375) 19.1 to <31.8 mm (321-375) 31.8 to <50.5 mm (293-331)	Class 2 <9 mm (341 min) 9 to <15 mm (311 min) 15 to <35 mm (285 min) 35 to <50 mm (262 min)	Bisplate High Impact Armour (HIA) Class 1 (290-390)
Class 4	370-430	MIL-A-12560H Class 4B (381 max)	No Equivalent	Bisplate High Toughness Armour (HTA) (370-430)
Class 5	420-480	MIL-A-12560H Class 4A (442 min)	Class 3A 5 to <50 mm (420-480)	Bisplate Ultra High Toughness Armor (UHTA) (420-480)
Class 6	470-535	MIL-A-46100D	Class 3 <15 mm (470-540) 15 to <35 mm (470-535)	Bisplate High Hardness Armor (HHA) (477-534)
Class 7	530-605	No Equivalent	Class 4 <15 mm (530-605) 15 to <50 mm (495-605)	No Equivalent
Class 8	560-655	No Equivalent	Class 5 (560-655)	No Equivalent

[1]Each hardness range in DEF (AUST) 8030 applies for all thicknesses from 3-35 mm, unless otherwise specified. Source: Dwight et al. (2007)

2008; Atapek, 2012). This will aid the further development and application of unified armour steel specifications that control armour steel properties over a wide range of steel hardness, Australian DEF (AUST) 8030 and UK DEF STAN 95-24 being good examples of such specifications.

Table 1 compares these specifications, the U.S. Military Specifications and the recently developed Bisalloy steel grades. The DEF (AUST) 8030 is a unified armour steel specification, which controls the mechanical and chemical properties over a full range of functional rolled homogenous armour steel classes. It is a performance-based specification, allowing the user the freedom to choose armour steel that best meets their needs while defining ballistic performance quality assurance requirements and, importantly, ensuring that the structural integrity of the resulting armoured structure will also meet a minimum standard (Cimpoeru and Alkemade, 2002).

Currently, the highest-performing US made steel alloys for armour piercing bullet protection are manufactured to MIL-DTL-46100E HHA with a hardness range of 477-534 Brinell Hardness Number (BHN) and to MIL-A-46099C Dual Hardness Armour (DHA) that is produced by roll-bonding a 601-712 BHN front plate to a 461-534 BHN back plate (U. S. Military Specification, 1987). The roll-bonded DHA steels are complex to produce and have known production limitations (Dwight, 2011).

Meanwhile, the microstructure of steel determines its physical and chemical properties under loading condition. For armour steel, the matrix having martensitic/bainitic tempered martensitic-bainitic structure determines the ballistic performance, which is usually achieved after application of austenisation and then quenching on low carbon and alloyed steel (Hu, 2002; Sangoy, 1988). Several studies had emphasized that a martensitic/bainitic structure and morphology of these phases, content of retained austenite, austenization/tempering conditions directly affected the final failure mode or ballistic performance of heat treated steels used as armour (Atapek, 2011 and 2012). On the other hand, selection of appropriate material and processing conditions, as well as the resulting microstructural and mechanical properties immensely affect the protective characteristics of the material under any dynamic loading (Deniz, 2010). The present study assessed the 6-mm imported SAN-armour steel plate against test projectile, 0.30 Calibre APM2 in order to evaluate and verify its ballistic property.

2. MATERIALS AND METHODS

The steel plate tested for this evaluation experiment has a thickness of 6mm and a dimension of 300mm by 500mm. This sample was selected at random from the short pieces that have comparable dimension (Atapek, 2011) for ballistic testing without setting up pre-test stress on the sample by cutting operation on the larger sheets.

2.1. Chemical analysis

Chemical analysis of the plate was conducted in accordance with the applicable method specified in ASTM A751 (U.S. Military Specification, 2006), using Optical Emission Spectrophotometer (PDA-700, Shimadzu, Japan) available at the Research and Development Centre, Defence Industries Corporation of Nigeria (DICON), Kaduna, Nigeria. The analysis was compared with the declared composition established in accordance with the requirements of MIL-DTL-46100E shown in Table 2.

2.2. Mechanical tests

Hardness test (Brinell hardness test) was conducted in accordance with ASTM E10, using a 10mm carbide ball and a 3000 kg load. Surface scale and decarburization was removed from the areas where the tests were made. However, not more than 1.5mm was removed from the test area (Dwight, 2011). Also, Charpy V-notch impact test for the sample was prepared and tested in accordance with ASTM E23. The Charpy V-notch impact test specimen was taken in the transverse (TL) orientation. In conforming to ASTM E8 the tensile strength and percent elongation were also determined. The percentage elongation was calculated by dividing the elongation at the moment of rupture by the initial gauge length and multiplying by 100. The minimum requirements values for impact strength as per MIL-DTL-46100E are 16.3J (transverse) and 19.0J (longitudinal).

2.3. Microstructure of the armour steel

A sample taken from the stock of the procured steel was prepared by metallographical method (Provide references where used in literature). The sample was prepared by grinding with 320, 600 and 1000 mesh size SiC abrasives in succession. Then, the ground surface was polished with 3μm diamond solution. Etching was carried out with nital (3% of HNO_3) to characterize the microstructure. Scanning Electron Microscope (ProX-20.120x, Phenom, Germany) obtained from Ahmadu Bello University, Zaria, Nigeria, was used for metallographic examination.

Table 2: Chemical Composition Requirements According to MIL-DTL-46100E4/

Element	Column A maximum limit for first article & production chemistry (weight percent)	Column B 5/ allowable range for future production lots (weight percent)
Carbon	0.32	3/
Manganese	None required, however if:	
	< 1.00	± 0.15
	> 1.00	± 0.20
Phosphorus	0.020 1/	3/
Sulfur	0.010 1/	3/
Silicon	None required, however if:	
	< 0.60	± 0.10
	> 0.60 to < 1.00	± 0.15
	> 1.00	± 0.20
Nickel	None required 2/	± 0.25
Chromium	None required, however if:	
	< 1.25 2/	± 0.15
	> 1.25	± 0.25
Molybdenum	None required, however if:	
	< 0.20 2/	± 0.035
	> 0.20	± 0.075
Vanadium	None required 2/	± 0.075
Boron	0.003	3/
Copper	0.25 2/	3/
Titanium	0.10 2/	3/
Zirconium	0.10 2/	3/
Aluminum	0.10 2/	3/
Lead	0.01 2/	3/
Tin	0.02 2/	3/
Antimony	0.02 2/	3/
Arsenic	0.02 2/	3/

1/ Phosphorus and sulfur should be controlled to the lowest attainable levels, but in no case shall the combined phosphorus and sulfur contents exceed 0.025 wt%.

2/ When the amount of an element is less than 0.02 wt% the analysis may be reported as [< 0.02 wt%].

3/ Product analysis values may not exceed those listed as the maximum limit.

4/ Elements not listed in table, but intentionally added, shall be reported.

5/ Values are actual tolerance limits NOT percent tolerances. The analysis from the First Article sample is the "Declared Chemistry" which is used to calculate the range.

Source: U. S. Military Specification (2008).

2.4. Test projectile

The corresponding test projectiles and plate obliquities required for various armour plate thicknesses under MIL-DTL-46100E are listed in Table 3. The weights and sizes of the various projectiles are shown in Table 4 while the detail description of the projectile applied in this research (0.30-cal. APM2) is shown in Figure 1, with the hardened steel core.

2.5. Ballistic tests

Ballistic tests were carried out on the plate in order to ascertain the potency of the armour plate against the projectile. Four shots were fired by a 0.30-calibre armour piercing projectile (high kinetic energy) with a velocity of 830 m/s from 20 m range against a 300 x 500mm sample of the steel plate.The plate was firmly clamped along the 300mm sides at 30° obliquity to the bullets.The test was carried out at the Quality Control (Shooting Range: weapon/ammunition testing section) of the Defence Industries Corporation of Nigeria, Kaduna, Nigeria.The parameters and effect of each impact were recorded.

The V_{50} ballistic limit was taken as the velocity at which an equal number of fair impact complete penetration (target is defeated) and partial penetration (target is not defeated) velocities are attained using the up-and-down firing method. Fair impact was defined as occurring when a projectile with an acceptable yaw strikes the target at a distance of at least two projectile diameters from a previously damaged impact area or edge of plate. A complete penetration (perforation) was determined by placing a 0.5mm 2024 T3 aluminium witness plate 152.6mm behind and parallel to the target. If any penetrator or target fragment strikes this witness plate with sufficient energy to create a hole through which light passes, the result was considered a complete penetration. A partial penetration is any impact that is not a complete penetration (U. S. Military Specification, 1997; 2008). This procedure was followed carefully during the firing test.

3. RESULTS AND DISCUSSION

3.1. Chemical compositions

The chemical analysis of the armour steel in the experiment shows that it contains(by weight %): C, 0.25; Mn, 0.93; Si, 0.18; Ni, 0.04; Co, 2.35; Cr, 1.2; Mo, 0.5; Nb, 0.08; V, 0.08; Ti, 0.06; B, 0.01; P, 0.01; S, 0.01 and Fe been the balance so that its composition is in agreement with the requirements specified in MIL-DTL-46100E on chemical composition of plates for the production of armour steel, as shown in Table 2.

3.2. Mechanical properties

The mechanical properties of the steel are as follows: tensile strength, 1290MPa; hardness, 483HBN; elongation, 10.1% and impact strength, 27J. The values are closely aligned with the main military standards of DEF (AUST) 8030, DEF STAN 95-24, the U.S. Military and Bisalloy Steels Grades Specifications as per Table 1.The assessed steel can be more classified as Class 6 of Armour Grade, according to Table 1.

3.3. Microstructural characteristics

Figure 2 shows the scanning electron microscope image of the etched experimental specimen. The matrix typically exhibits a tempered bainite microstructure.

Table 3: Thickness ranges and corresponding test projectiles for Article testing (30° obliquity)

Nominal Thickness Range (mm)	Test Projectile
3.00 to 7.62 inclusive	0.30-cal. APM2
7.62 to 15.0 inclusive	0.30-cal. APM2
15.0 to 19.4 inclusive	14.5-mm B32
19.4 to 28.7 inclusive	14.5-mm BS41

Source: U. S. Military Specification (1988 and 2008)

The regions in gray contrast denote the ferritic matrix which refers to decomposed and coarsened lath due to tempering. Intensive precipitates having higher hardness compared to the matrix are seen in dark contrast, since they have lower reflective index (Atapek, 2012). The grain boundaries are clearly seen in the microstructures. Therefore, its martensitic/bainitic structure gives the experimental steel plate the ballistic tendency to be used for armour application.

3.4. Ballistic performance

Table 5, according to MIL-DTL-46100E, shows the minimum V_{50} velocities against various thicknesses of plates. The experimental plate (Figure 3) is 6mm (approximately 0.235inches) with an equivalent minimum required ballistic limit velocity of 648m/s (2126ft/sec).

The V_{50} ballistic limits observed for the armour steel plate had an average of 793m/s recorded. The ballistic performance of experimental plate has therefore exceeded the minimum velocity accepted (648m/s).

For armour to be accepted into service in the U.S., it must meet the requirements of MIL-DTL-46100E. This result shows that the ballistic limit was met and exceeded that required in the standard for the particular steel thickness. Conclusively, the plate tested to the stated specification "passed

4. CONCLUSION

The microstructure, mechanical properties and the ballistic performance characterizations of acclaimed ballistic armour steel have been examined. The steel showed satisfactory Charpy impact resistance (27J), hardness value (483HBN) and V_{50} ballistic limit (793m/s) of the plate against steel-cored armour-piercing projectiles in accordance to established standards, MIL-DTL-46100E. The armour steel plate has proven to be effective in resisting penetration from bullets fired from a distance of 20 meters, without perforation.

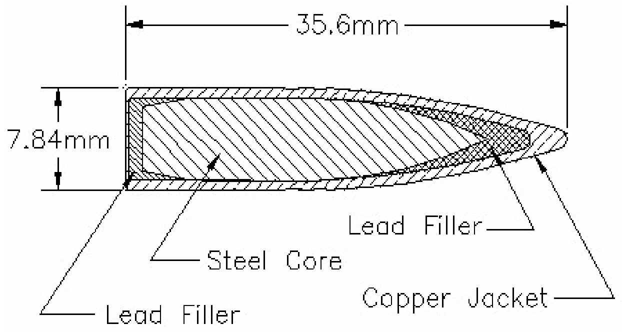

Figure 1: 0.30-cal. APM2 with the hardened steel core

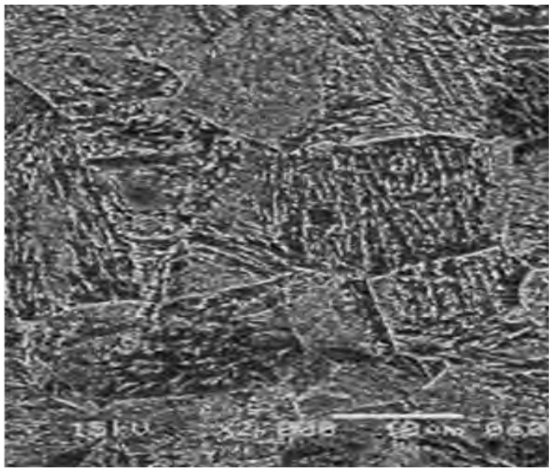

Figure 2: Scanning electron microscope image of the tempered bainite microstructure.

Table 4: Geometries and weights of projectiles with their corresponding cores

Projectile Core / Projectile Type	Length (mm)	Diameter (mm)	Weight (g)	Length (mm)	Diameter (mm)	Weight (g)
0.30-cal. APM2	35.3	7.85	10.8	27.4	6.2	5.3
0.50-cal. APM2	58.7	12.98	45.9	47.5	10.9	25.9
14.5-mm B32	66.3	14.86	64.1	53.1	12.4	41.0
14.5-mm BS41	52.6	14.94	63.2	32.3	10.9	37.9

Source: U. S. Military Specification (2008)

Table 5: Minimum required ballistic limits - calibre .30 AP M2 projectiles @ 30^0 obliquity

Thickness		Required BL(P)	
Inches	mm	ft/sec	m/sec
0.100	2.54	616	187.76
0.200	5.08	1839	560.53
0.225	5.715	2050	624.84
0.230	5.842	2088	636.42
0.235	5.969	2126	648
0.240	6.096	2162	658.98
0.245	6.223	2197	669.65
0.250	6.350	2232	680.31

Source: U. S. Military Specification (1987)

Figure 3: Frontal face- showing the plate's ballistic resistance against 0.30 calibres

REFERENCES

Atapek, S. H. "Ballistic Impact Behaviour of Quenched and Tempered Steels" International Iron & Steel Symposium, April 02-04, 2012, Karabük, Turkey: 413-419, 2012.

Atapek, S. H. and Karagoz, S. "Ballistic Impact Behaviour of a Tempered Bainitic Steel Against 7.62 mm Armour Piercing Projectile", Defence Science Journal, 61(1): 81-87, 2011.

Cimpoeru, S. J. and Alkemade, S. J. "Guidelines for Effective Armour Material Specifications for Defence Applications". Technological and Research Developments in Welded Defence Equipment Conference, Wtia, 2002.

Deniz, T. "Ballistic Penetration of Hardened Steel Plates" Published M.Sc. Thesis, Mechanical Engineering Department, Middle East Technical University. August, 2010.

Dwight D. S. *et al.* "Development and Ballastic Testing of a New Class of High Hardnes Armor Steel" AMMTIAC Quarterly, 4(4): 3-6, 2011.

Dwight, D. S., William, A. G. and Matt, S. B. "Ballistic Testing of Australian Bisalloy Steel for Armour Applications". A Reprint from The Proceedings of the 23rd International Ballistics Symposium, Tarragona, Spain, 16 June 2007: 1-10, 2007.

Hu, C. J., Lee, P. Y. and Chen, J. S. "Ballistic performance and microstructure of modified rolled homogeneous armor steel", Journal of the Chinese Institute of Engineers, 25(1): 99-107, 2002.

Maweja, K. and Stumpf, W. "The design of advanced performance high strength low-carbon martensitic armour steels: Part-1". Mechanical property considerations. Mat. Sci. Engg., A, 2008, 485(1-2): 140-53, 2008.

Sangoy, L., Meunier, Y. and Pont, G., "Steels for ballistic protection", Israel Journal of Technology, 24: 319-326, 1988.

U. S. Military Specification "Armor Plate, Steel, Roll-Bonded, Dual Hardness (0.187 Inches to 0.700 Inches Inclusive)" MIL-A-46099C, 1987.

U. S. Military Specification "Armour Plate, Steel, Wrought, High-Hardness 2008" MIL-DTL-46100E, October 2008.

U. S. Military Specification "V_{50} Ballistic Test for Armor," Department of Defense Test Standard, MIL-STD-662F, December 1997.

U.S. Military Specification "Armour Plate, Steel, Wrought, High-Hardness" MIL-DTL-46100E (MR), 2006.

U.S. Military Specification, "Amendment 3, Armour Plate, Steel, Wrought, Homogeneous (For use in Combat Vehicles and Ammunition Testing)" MIL-A-12560H (MR), 2000.

William, G. *et* al. Development and ballistic testing of a new class of auto-tempered high hard steels under military specification MIL-DTL-46100E. TMS San Francisco, CA, 15-19 February, 2009: 1-8, 2009.