DETERMINATION OF THE MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF AN ARMOUR STEEL FOR HIGH IMPACT PERFORMANCE

BY

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(MEE/11/0403)

A PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF BACHELOR OF ENGINEERING (B.ENG) IN MECHANICAL ENGINEERING

TO

DEPARTMENT OF MECHANICAL ENGINEERING
FACULTY OF ENGINEERING
FEDERAL UNIVERSITY, OYE – EKITI.

SEPTEMBER, 2016.

CERTIFICATION

This is to certify that this project was written by ASIFA EMMANUEL VICTOR (MEE/11/0403) under my supervision and is approved for its contribution to knowledge and literary presentation. All sources of information are specifically acknowledged by means of references, in partial requirements for the award of Bachelor of Engineering (B.ENG) degree in Mechanical Engineering, Federal university Oye-Ekiti, Ekiti, Nigeria.

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ACKNOWLEDGMENT

All glory and honour is ascribed to God Almighty the maker of Heavens and the earth who saw me through life and daily loaded me with benefits and wisdom to carry out this project.

It is a pleasure to thank the many people who made this project possible. I am most grateful to my project supervisor Engr. Sanusi O.M, for accepting me as his student and allowing me to work in such excellent conditions. But above all, I am thankful for his kindness, guidance, support and encouragement.

I wish to thank Engr. Uzor Joel of the University of Lagos, Lagos-state for passing onto me a little of his expertise and enthusiasm about mechanical spectrometry for his helpful theoretical discussions and for assisting in the chemical composition test.

I owe a debt of gratitude to Engr. Oluwamuyiwa Olateju of the Engineering Materials Development Institute, Akure state for his unwavering help and support in carrying out the microstructural, hardness and tensile tests.

I wish to thank Engr. H.A Benjamin of Afe Babalola University, Ado-Ekiti for his assistance in carrying out the impact test and making sure I get quantitative results.

I am indebted to every staff and student of the mechanical department of the Federal University Oye-Ekiti for and unquestionable support.

Immense thanks to my big family, who let me go so far from them. I thank them for all their love, support and prayers.

ABSTRACT

The research evaluates the chemical, mechanical and microstructural characterization of an armour steel sourced from a scraped armoured vehicle in order to develop local content in the armouring technology. Chemical analysis, optical microscopy and mechanical tests were employed to examine the microstructural and mechanical properties of a low carbon armour steel. Chemical analysis showed the elemental constituents and the exact weight per percentage of each element present in the test sample as per MIL-DTL-12560J standards. Microstructural analysis was carried out on etched sample of the plate which exhibited the desired bainitic microstructure. Dispersed within the bainitic microstructure were high carbon micro constituents consisting of iron carbides and pearlite. Then hardness, tensile and impact strength of the plate were assessed following standard procedures. The results showed that the specimen tested has a tensile strength of 1291MPa, a hardness value of 479BHN, 11% elongation, and impact resistance of 27.15J. The mechanical performance of the plate was in consonance with the minimum mechanical requirements of MIL-DTL-12560J standards. This study, therefore established that the tested armour steel plate is effective for high impact performance.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND TO THE STUDY

An Armour is a protective covering made of hardened materials intended to prevent damage from being inflicted to an object, individual, or vehicle by direct contact weapons or projectiles, usually during combat, or from potentially dangerous environment (Tansel, 2010). Armour technology are used in military vehicles and equipment, civil vehicles, bank counters and vaults, doors, window frames, walls, money exchange offices, secured containers, shooting gallery devices to mention a few (Villacero, 2015). Personal armour is used to protect soldiers and war animals. Armour materials can be classified into three main groups, namely metallic, ceramic and polymeric material (Tansel, 2010).

An armour steel have properties like; high resistance to perforation and ballistic impact; easy fabricability; adequate fatigue and wear resistance under service conditions. Hardness is an important feature for the materials used for armour strategy. (Sangoy *et al.*, 1988) reported that high hardness of a given armour steel directly determines the ballistic performance and perforation mode. It is generally considered that armour steels having high toughness will be very useful to resist ballistic impacts without being fractured (Acarer *et al.*, 2008). As it is well known, alloying and also heat treatments affect the toughness of the material (Karagöz *et al.*, 2010).

The trends of worldwide armour community is currently accelerating efforts to deliver lightweight armour technologies that can defeat armour piercing (AP) projectiles at reduced areal weights and that they are available across a large industrial base (Baloh *et al.*, 2010). While many of these programs involve the application of lower density metals, such as aluminum and titanium, the selection of steel alloys is still competitive for many ballistic and structural applications. The ability to produce armour components in both commercial and military operational areas with available equipment and personnel is a major advantage of steel based solutions. To meet these requirements, the worldwide armour community has increased the availability of quenched and tempered armour steels by updating current steel military specifications (Atapek, 2011).

The specifications for armour steel plate are actually determined in terms of mechanical properties which includes hardness, yield strength, tensile strength, elongation and assessed by ballistic tests.

Amongst these properties the hardness- of the steel is considered to be the main indicator of ballistic performance (ISCOR, 2003).

This research therefore focuses on the studying of mechanical and microstructural properties of an armour steel in order to compare it results with established values and as well as studying the characteristics for possible domestication of armour steel technology in Nigeria.

1.2 STATEMENT OF PROBLEM

With the ever increasing level of crime and terrorism in Nigeria, armoured mobility has been the priority of governments, corporate organizations, VIPs and ordinary citizens. This menace will continue to increase if necessary machineries are not put in place to combat the situation. Nigeria continues to face attacks whose activities have claimed over 11,000 lives in the last five years due to insurgency, despite a total sum of N4.62trillion allocated to the federal security sector in the past five years (Joshua, 2015). According to Abgro (2014), Nigerians spend about N10bn annually on armoured cars. Before the latest auto policy review, as at 2012, Nigerians imported 200,000 used-vehicles and 80,000 new-vehicles at an annual cost of N400bn (Agbro, 2014). Little research has been conducted towards armour technology in Nigeria which in turn fosters the need to import these armoured cars and minimizes the usage of local contents in Nigeria.

1.3 JUSTIFICATION OF THE RESEARCH

There are enough natural resources available in Nigeria. If local contents are patronized and the auto policy review properly implemented, this may also force the country to develop its steel sector, given that steel makes about 60% of vehicle components. If research and development are directed to this area, established standard data for armour applications requirement can be provided to Nigerian steel manufacturers to implement on our indigenous materials to facilitate the applications of armour technology in Nigeria.

1.4 AIM AND OBJECTIVES

1.4.1 AIM

This work understudies the mechanical and microstructural properties of an armour steel to determine its high performance characteristics and compare it properties with established values and as well as studying the characteristics for possible domestication of armour steel technology in Nigeria.

1.4.2 OBJECTIVES

The following objectives are to be achieved during the course of this project:

i. Source for the armour steel plate.
ii. Chemical characterization of the armour steel.
iii. Microstructural studying of the armour steel.
iv. Mechanical characterization of the armour steel.
v. Compare the results with established standards MIL-DTL-12560J to determine its mechanical performance.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Metals and their alloys, ceramics, polymers and composite materials can be used as armour materials in structural protection technology. The conceptions such as hardness, strength and toughness are the main features for the ballistic performance of a given material (Showalter *et al.*, 2000). Recently, defense industry has been trying to find out materials having excellent ballistic performance under any defined threat and all attempts focus on the design of new alloys/materials, single or multi composite systems, processing techniques and secondary treatments. For this purpose, the search and development studies on blast and penetration-resistant materials (BPRMs) are very popular in many disciplines (Atapek *et al.,* 2011).

Many metals make great BPRMs, and the most common ones include steel (ferrous alloys), aluminum and titanium alloys. The purpose of metals in structural protection is often two-fold: protection against fragments and secondly, maintaining structural integrity. Metals are highly useful in protecting structures against explosions because of their inherent strength, toughness and energy absorption capability. The most known alloy as protection is the armour steel which is an indispensable material for many civilian applications, where high security is needed, like money chests, defense walls for banks, private armoured vehicles, etc. (Maweja, 2005). Armour steels due to their high strength, hardness and toughness properties (Matsubara *et al.*, 1972) have a high level of energy absorption capability under any interaction with a projectile or a particle having high velocity. The only armour grade steel, which is currently used for structural applications, is the rolled homogenous armour (RHA). An armour steel should have properties like (i) high resistance to perforation and ballistic impacts, (ii) easy fabricability, (iii) adequate fatigue and wear resistance under service conditions. Hardness is an important feature for the materials used for armour strategy. (Sangoy *et al.*, 1988) reported that high hardness of a given armour steel directly determines the ballistic performance and perforation mode. A number of studies have revealed that the hardness has a direct effect on the ballistic performance of the materials (Dikshit *et al.*, 2000). On the other hand, toughness is another critical property for a given armour material under a dynamic attack of projectiles having high kinetic energies. It is generally considered that armour steels having high toughness will be very useful to resist ballistic impacts without being fractured

(Acarer *et al.*, 2008). As it is well known, alloying and also heat treatments affect the toughness of the material (Karagöz *et al.*, 2010).

2.2 Armour Materials

Armour materials can be classified into three main groups, namely metallic, ceramic and polymeric materials (Tansel, 2010).

2.2.1 Metallic Armours

Metals are still the most widely used materials in armour design. The main advantage of these 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 (Maweja, 2005).

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 (Hazell, 2006).

Steel armour can be studied in four main groups which are:

- Rolled Homogeneous Armour (RHA)
- High Hardness Armour (HHA)
- Variable Hardness Steels and
- Perforated Armour.

2.2.1.1 Rolled homogeneous armour (RHA)

This is usually used in depth of penetration testing (Hazell, 2006) as a benchmark material. Therefore it is used to describe and compare the performance of different armour systems or materials. The chemical composition, classification of RHA and the mechanical properties of different classes of armour plate according to UK Ministry of Defense Standard for Armour Plate (DEF STAN 95-24/3) are given in Table 2.1, Table 2.2, Table 2.3, Table 2.4, Table 2.5 and Table 2.6.

Table 2.1: Required Chemical Composition of RHA

Element	C	Mn	Ni	Cr	Mo	S	P
Weight	0.18-0.32	0.60-1.50	0.05-0.95	0.00-0.90	0.30-0.60	0.015(max)	0.015(max)

Source: DEF STAN 95-24/3, 2004.

Table 2.2: Classification of RHA

Classification	Description	Hardness (BHN)	UTS (MPa)	Elongation (%) Min
Class 1	Readily weldable steel subjected to structural loads.	262-311	895-1,050	15
Class 2	Readily weldable steel to protect against AP ammunition	255-341	895-955	14-16
Class 3	Readily weldable higher hardness steel manufactured in thin sections.	470-540	1,450-1,850	8
Class 3A	Readily weldable higher hardness steel manufactured in thin sections.	420-480	1,200-1,600	9
Class 4	Higher carbon and alloy content higher hardness armour for thick sections.	475-605	1,450-2,000	7
Class 5	High alloy content/hardness armour	560-655	1,800-2,400	6

Source: DEF STAN 95-24/3, 2004.

Table 2.3: Mechanical Properties for Class 1 and 2

Class	Nominal thickness (mm)	Hardness (Min-BHN)	UTS (MPa)	Elongation (%) min.	Charpy (J) " V" Notch Min RT	Charpy (J) " V" Notch Min-40°C
1	ALL	262-311	895-1050	15	42	40
2	3 to less than 9	341			30*	20
2	9 to less than 15	311			30*	20
2	15 to less than 35	285	955	14	30	25
2	35 to less than 50	262	895	15	35	30
2	50 to less than 70	262	895	15	42	30
2	70 to less than 100	255	850	16	50	35
2	100 to less than 160	255	850	16	65	40

Source: DEF STAN 95-24/3, (2004).

Table 2.4: Mechanical Properties for Class 3

Nominal Thickness (mm)	Hardness (BHN)	UTS (MPa)	Elongation (%) Min.	Charpy (J) "V" Notch Min-40°C
3 to less than 15	470-540	1450-1850	8	16*
15 to less than 35	470-535	1600-1850	8	29

* For reduced section specimens a minimum value of 0.20 J/mm² applies.

Source: DEF STAN 95-24/3, (2004).

Table 2.5: Mechanical Properties for Class 4

Nominal Thickness (mm)	Hardness (BHN)	UTS (MPa)	Elongation (%) Min	Charpy (J) "V" Notch Min -40°C
3 to less than 15	530 – 605	1600-2000	7	12*
15 to less than 29	495 – 605	1550 – 2000	7	12
29 to less than 50	495 – 605	1550 – 2000	7	12
50 to less than 70	475 – 605	1550 – 2000	7	16
70 to less than 100	475 – 605	1450 – 2000	7	16
100 to less than 150	475 – 605	1450 – 2000	7	16

*For reduced section specimens a minimum value of 0.15 J/mm² applies.

Source: DEF STAN 95-24/3, 2004.

Table 2.6: Mechanical Properties for Class 5

Nominal Thickness (mm)	Hardness (BHN)	UTS (MPa)	Elongation (%) Min.	Charpy (J) "V" Notch Min -40°C
3 to less than 15	560 – 655	1800 – 2400	6	5*
15 to less than 39	560 – 655	1800 – 2400	6	5
39 to less than 50	560 – 655	1800 – 2400	6	5

* For reduced section specimens a minimum value of 0.05 J/mm^2 applies.

Source: DEF STAN 95-24/3, 2004.

2.2.1.2 High hardness armour (HHA)

This is the name given to a class of homogeneous steel armour which have hardness values exceeding 430 BHN (Hazell, 2006).

2.2.1.3 Variable hardness steel

This plate introduces some advantages with varying through-thickness properties (Maweja, 2005). By surface hardening one side of a thick low-carbon steel plate, it is possible to incorporate both hard disruptive and tough absorbing properties in a single material (Hazell, 2006). The main advantage is that, the more ductile backing layer is able to arrest crack propagation in the armour plate while the hard front layer is able deform or fracture the threat. The effectiveness of dual-hardness armour (DHA) is given by a comparison in Table 2.7 (Ogorkiewicz, 1991). It can be seen that DHA is more efficient compared to HHA in defeating steel cored 7.62 AP bullet.

Table 2.7: Density, thickness and areal density values required to protect against 7.62 mm AP bullets at normal incidence.

Armour Steel	Density (*kg/m³*)	Thickness (mm)	Areal Density (*kg/m²*)
RHA (380 BHN)	7830	14.6	114
HHA (550 BHN)	7850	12.5	98
DHA (600-440 BHN)	7850	8.1	64

Source: Ogorkiewicz, 1991.

2.2.1.4 Perforated armour

In perforated armour holes are introduced into the steel plates. These holes in high hardness steel plate has been shown to be an effective way of disrupting and fragmenting incoming projectiles. This mechanism can be regarded as edge effect.

Aluminum alloys also provide a versatile choice for an armour design engineer. The main advantage is that, it has a relatively low density while the tensile strengths range from 60 – 600 MPa. It can be deduced that equal mass of aluminum armour will have a larger volume compared to steel, which leads to improvement in rigidity. However, there are some disadvantages associated with aluminum alloys. The harder alloys that are suitable as armour are susceptible to stress corrosion cracking (Hazell, 2006). This type of failure occurs when the aluminum alloy is attacked by a corrodant while it is subjected to tensile stress. The magnitudes of stresses required to start a failure is lower than that of yield strength and the residual stresses induced during machining, assembly or welding can lead to failure. These alloys also possess a lower spall strength than steel so that they are prone to scabbing. The ballistic grade form (Ti-6Al-4V) of titanium also provides a good alternative to steel. It possesses a relatively low density (4.45 $g/cm3$) while it maintains high strength and hardness (UTS 900 – 1300 MPa, BHN 300 – 350). However, high cost related with titanium alloys is a prominent shortcoming.

2.2.2 Ceramic Armours

It can be anticipated that the resistance of a given material to penetration mainly depends on its compressive strength (Rosenberg *et al.*, 2009). Ceramic materials, which possess high compressive strength and hardness values are good candidate materials as for the armour designer because of their relatively low densities (Hazell, 2006). High strength ceramics such as alumina, boron carbide and silicon carbide exhibit compressive strengths that are in order of magnitude higher than those of metals. Then, it seems plausible to make an assumption that ceramic faced targets will be efficient for armoured protection (Rosenberg *et al.*, 2009). The costs of ceramic tiles are taken into consideration besides its performance. A comparison of some ceramic materials with prices are given in Table 2.8 (Roberson, 2004).

Table 2.8: Relative cost of ceramic materials for armour applications

Ceramic	Bulk Density (kg/m^3)	Hardness (HV)	KIC[a] ($MPa.m^{\frac{1}{2}}$)	Relative cost
98 (%) Al_2O_3	3,800	1,600	4.5	1.0
RB[b] SiC	3,100	1,200/2,200	≈4.5	2.5
Sintered SiC	3,150	2,700	3.2	4.5
HP[c] SiC	3,220	2,200	5.0	9.0
HP B4C	2,520	3,200	2.8	16.0

[a]Fracture Toughness

[b]Reaction Bonded

[c]Hot Pressed

Source: Roberson, 2004.

2.2.3 Polymeric Armours

Polymeric composite materials possess high specific strength and specific stiffness and they are able to absorb significant part of kinetic energy induced by projectile impact. They also have relatively lower densities. These materials consist of laminates of matrix bonded reinforcing fibers. The function of the matrix is to provide a medium for the diffusion of load to the stronger and stiffer fibers. Typical fiber materials are S-glass, E-glass, aramid, carbon and boron. Some properties of these materials are presented in Table 2.9.

Table 2.9: Properties of some fiber materials

Fiber	Bulk Density (kg/m^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Failure Strain (%)
Aramid (low modulus)	1,440	2,900	60	3.6
Polyethylene (high modulus)	970	3,200	99	3.7
E-glass	2,600	3,500	72	4.8
S-glass	2,500	4,600	86	5.2
Carbon (high strength)	1,780	3,400	240	1.4

Source: Edwards, 2000

2.3 ALLOY DESIGN FOR STEEL

The elements likely to be found in armour steels as well as their potential effects on the microstructure and mechanical properties, are presented in Table (2.10)

2.4. SPECIFICATION FOR AN ADVANCED PERFORMANCE ARMOUR STEELS

A good armour martensitic steel should have a fine and homogeneous microstructure consisting of a low temperature tempered martensite (Maweja, 2005). Furthermore, such material must be clean with neither inclusions nor carbide precipitates on grain boundaries (Maweja, 2005). He formulated the chemical composition presented in table 2.11 for the development of an advanced armour plate steel with a superior ballistic performance:

Table 2.10. Alloying elements found in armour plate steels and their effects on microstructure and mechanical properties.

Element	Effect	Proposed specification
C	High C content increases the volume fraction of retained austenite after quenching to martensite. Increases the micro-hardness of the martensite.	0.38% - 0.45%
Mn	Improves the hardenability of the steel. Weak carbide former.	0.50% - 2.0 %
Mo	Only the metastable Mo_2C provides secondary peak hardening by tempering at about 500°C. Mo2C forms by separate nucleation on dislocations.	Not applicable 0.6% maximum
Ni	Solid solution hardening. Increases the precipitate/matrix misfit by modifying the lattice spacing of the matrix. Grain refiner, decreases the DBTT. Has a strong effect on decreasing the AC1.	2% - 4.0%
Cr	Cr is effective in retarding the softening from Fe3C in tempering by forming M3C. M7C3 has little strengthening effect.	1.5 %
Cu	Increases the matrix precipitation of Cu, apparently due to a heterogeneous nucleation mechanism on vacancy-Cu atom combinations.	0.3%
Si	Reduces the lattice spacing of the ferritic matrix and increases the precipitate/matrix misfit. Delays the decomposition of the martensite and the precipitation of the transition carbides upon tempering. Increases the corrosion resistance.	1.2% maximum
P	Segregates to grain boundaries	Unwanted <0.005%P
S	Segregates to grain boundaries	Unwanted.
N	Increases the hardenability, decreases the Ms temperature and forms coarse carbonitrides.	Unwanted

Source: ISCOR, 2003

Table 2.11: The optimum chemical composition range for advanced performance armour steels

Element	% C	% Mn	% Si	% Mo	% Cr	% Ni	% Cu	% P	% S
Range in weight percentage	0.38-0.43	0.4-2.0	0.4-1.2	0.4-0.6	0.4-1.5	1.0-4.5	< 0.2	< 0.005	<0.005

Source: Maweja, 2005.

He suggested the following points:

I. The martensite start temperature of the steel should be lower than 210°C;

II. The volume fraction of retained austenite in plate martensite should be higher than 1%;

III. The heat treatment should consist of austenitisation at temperatures between 850 and 950°C for less than 1 hour, followed by water quenching to room temperature;

IV. Tempering should be undertaken at temperatures ranging from 150 to 180°C for 20 to 60 minutes when the Silicon content is lower than 0.6%. The tempering temperature may be raised to 300°C when the Silicon content is higher than 1%;

V. The design methodology should be based on the Yield strength/ Ultimate Tensile strength (YS/UTS) ratio which should preferably be- below 0.6 as well as on a value of the Ballistic Parameter of 0.018 to 0.060 to predict the ballistic performance;

VI. Small size and thin armour plates should be preferred to reduce the risk of mechanical resonance of the armour plate with the firing frequency;

VII. Manganese sulphide and coarse carbides are detrimental to ballistic performance as well as to mechanical properties of the tempered plates; and

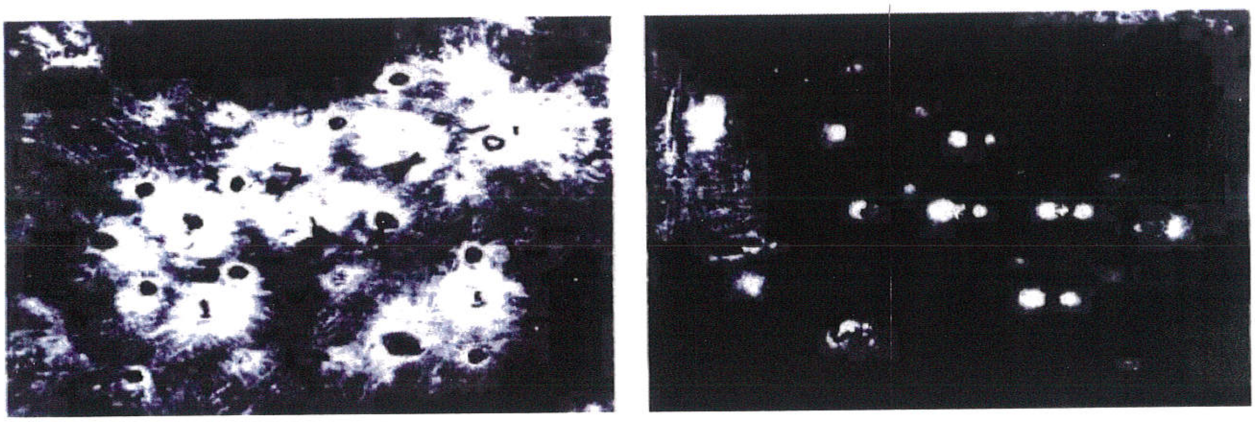
VIII. Under these conditions armour steels with a Brinell hardness of 475 BHN and a Charpy impact energy at -40°C as low as 10 Joules, are acceptable.

2.5. BALLISTIC (HIGH IMPACT PERFORMANCE) MATERIAL

Armour plate is heat treated to provide maximum resistance to ballistic perforation. The microstructure must be homogeneous throughout the section thickness and without inclusions that would act as crack initiators (Maweja, 2005). The external surface can present a higher hardness for resistance against penetration and compressive impact, whereas the internal surface could have a higher tensile strength (Wolsky *et al.*, 1982).

Cast armour has always been more resistant ballistically than rolled armour due mainly to the fundamental difference in mechanical and metallurgical properties between rolled and cast steel (Wolsky *et al.*, 1982). However production of armour plate is not feasible in cast forms (Maweja, 2005). It is possible to design a casting with smoother contours and higher obliquities than a flat plate, although normally heavier than a corresponding structure fabricated from rolled plate and in many cases with equal or even improved ballistic protection. Cast homogeneous steel armour is still used on Army Combat Vehicles under MIL-S-11356 to produce such components as hulls, turrets, cupolas, hatch covers, etc.

A large amount of empirical data obtained from a variety of tests confirmed that the armour strength or hardness of the steel is a very important parameter in resisting ballistic penetration (Maweja, 2005). According to this design philosophy the candidate armour material should exceed the hardness of the projectile (Wolsky *et al.*, 1982).This can be achieved primarily by thermal or thermomechanical processing (Maweja, 2005). The assessment criterion of ballistic resistance is that of "no visible light to pass through the impacted plate after the test" as illustrated by Figure2.0 (Wolsky *et al.*, 1982).



(a) FRONT (b) REAR

Figure.2.0: (a) and (b), multiple ballistic impact capability of armour plate made from a unidirectionally solidified ingot at a hardness in excess of 55 HRC. Light spots show the difference in sizes between the openings in the front and the rear faces of the impacted plate.

The increase in the ballistic performance versus hardness as a function of technological developments is shown in Figure 2.1.

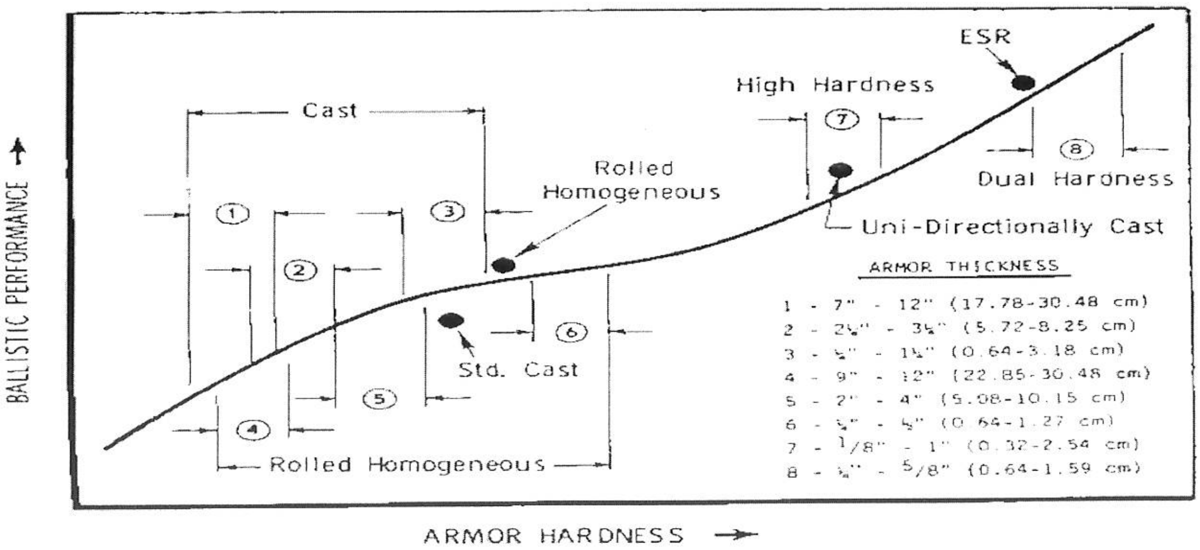


Figure.2.1: Relationship between armour hardness and ballistic performance (Wolsky *et al.*, 1982).

There are several additional factors to consider in the choice of alloy for armour plate but the major consideration would be that it should be effective in the field, and it should be light, which in turn gives a variety of advantageous secondary effects (Maweja, 2005).

Above all, the armour plate must also be cost-effective (Maweja, 2005). Other considerations are that the armour plate should be amenable to modern fabrication and construction techniques and be readily weldable and capable of being produced in a variety of shapes (Maweja, 2005). Bulk is an important factor because if the armour is bulky even though its area density is low, it will be difficult to provide sufficient room under the armour to meet volume requirements for the crew, gun, ammunition, fuel and power train (Maweja, 2005). For many years various alloy steels have measured up to this requirement very well. Armour application for these steels is well understood and can be made with optimization of various properties by changing the proportion and presence of the alloying elements (Maweja, 2005).

Although steel is a dense material with a larger area density (i.e. mass per unit area) comparatively to other armour materials, it does offer very good levels of protection against KE (Kinetic Energy) and HESH (Highly Explosive Squash Head) attacks, but its performance against HEAT (Highly Explosive Anti-Tank) attack is considerably reduced (Wolsky *et al.*,1982). Most alloy steels contain some or all of the elements Manganese, Chrome, Nickel, Molybdenum and Vanadium to give the correct blend of high strength and resistance to fracture or toughness (Maweja, 2005).

The major problem with all armour is that if the energy from the projectile is not to be transferred from the armour to the supporting structure then a way has to be found to dissipate the energy before this happens or the secondary effect may be equally fatal (Maweja, 2005).

Experience indicates that homogeneous steel armour (i.e. not a layered combination made from layers of different steels) should be made as hard as possible for defeating small arms and armour piercing (AP) ammunition (Maweja, 2005). However, as homogeneous steel becomes harder it also becomes more brittle and as the material becomes more brittle, its ballistic limit cannot be measured due to severe fracture of the armour (Maweja, 2005). Thus, limits on homogeneous armour hardness have to be established to prevent shatter of the armour due to embrittlement, but not necessarily because of strength limitations on the ballistic limit. This important fact has formed the basic guideline for improved steel armour development programs. That is, to increase the steel armour's ballistic limits by increasing its hardness without increasing the tendency towards brittle failure. An armour hardness of at least 58 to 62 Rockwell C would be required to induce shattering of the projectile upon impact (Wolsky *et al.*, 1982).

Various definitions for complete and partial penetration are illustrated in Figure 2.2.

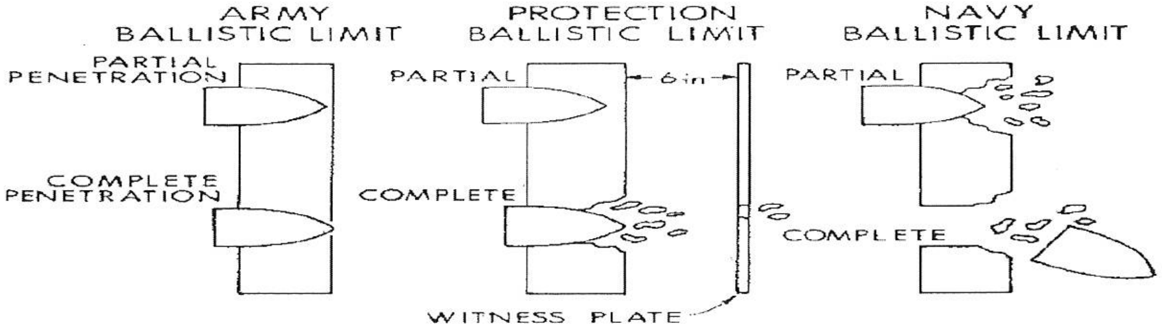


Figure 2.2. Definitions of perforation and partial penetration for defining the ballistic limit.

The ballistic superiority of steels of higher metallurgical quality has been demonstrated often. The development of unidirectional solidified wrought steel armour showed that cast steels with superior ductility could be produced by unidirectional solidification, which produces a cast structure in which columnar grains extend from the chill surface completely through the casting. The resulting solidified steel ingots have been found to be virtually free of gross porosity and with a much finer segregation pattern, factors that contribute to higher ductility (Wolsky *et al.*, 1982).

The homogenization heat treatment, which consists of holding the casting at 850°C for 64 hours, would virtually eliminate alloy segregation. Steels of armour composition have been produced by this process and have been homogenized, rolled, and heat-treated to hardness levels ranging from 50 to 60 HRC.

The important requirement of structural tank armour is that it should maintain structural integrity at sub-zero temperatures when impacted by overmatching artillery rounds. Test plates are inspected after proof testing for their ability to withstand fracture, spalling, and cracking. The long-standing empirical materials specification, which applies to structural tank armour and its ability to maintain integrity at low temperatures, requires that the material must have a minimum of 27.12 J (20 ft-lbs) transverse Charpy V-notch impact energy at a temperature of -40 0 C (Wolsky *et al.*, 1982).

2.6 Mechanical and Chemical Properties of Tempered Martensitic Steels

For an alloy steel with the chemical composition shown in Table 2.1, results on the tempering of the martensite have been found by Woei-Shyan *et al* (1999).

Table2.12: An alloy steel chemical composition

Elements	C	Si	Mn	Ni	Cr	Mo	P	S
Wt.(%)	0.39	0.24	0.61	1.46	0.67	0.17	0.021	0.006

Source: Woie-Shyan *et al.*, 1999.

(Woie-Shyan *et al.*, 1999) have also found the effect of tempering of the martensite on hardness and ultimate tensile strength as presented in figure 2.4 and 2.5:

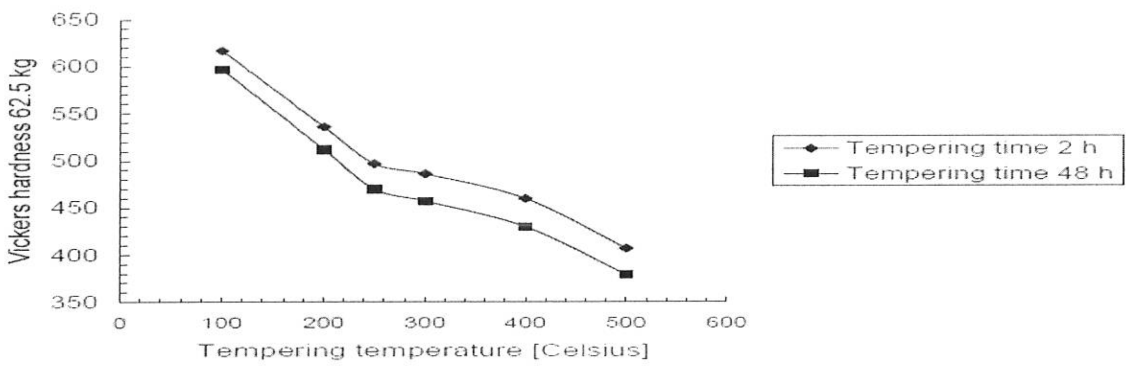


Figure. 2.3: Effect of tempering temperature and time (Woie-Shyan *et al.*, 1999)

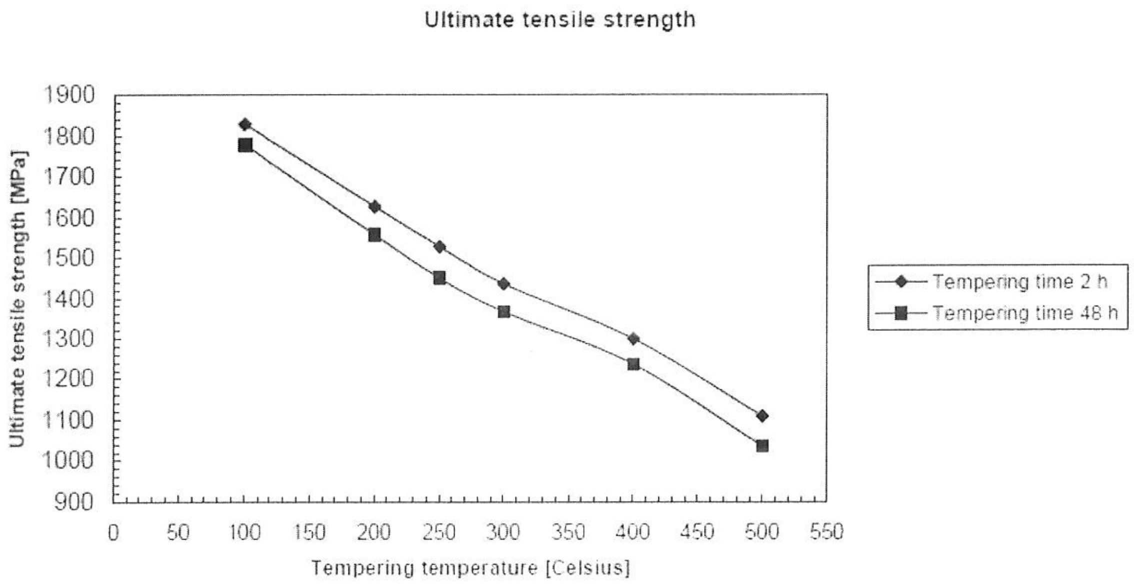


Figure 2.4: Variation of hardness and ultimate tensile strength with the tempering temperature of a low carbon steel (Woie-Shyan *et al.*, 1999)

In the as-quenched condition, the material has the highest level of strength and hardness but its ductility is the lowest, because of the presence of untempered martensite. A large amount of distortion occurs during the formation of the platelets of martensite, which leads to a rapid increase in strength and hardness. The thermal instability of interlath austenite after tempering often leads to the formation of carbide films, which is a fairly general cause of tempered martensite embrittlement, (Woei-Shyan *et al.*, 1999) correlated a loss in toughness after tempering at 300 *0C* with the retained interlath austenite and the formation of interlath carbide films that are decomposed from the lath boundary retained austenite. Table 2.13 shows the required elements present in an armour steel along with its percentage per weight in accordance with MIL-DTL-12560J (2009).

Table 2.13: Chemical composition requirement according to MIL-DTL-12560J (MR)

Element	Column A Maximum Limit (Weight %)	Column B 5/ Allowable Range (Weight %)
Carbon Class 1, 2, 3 & 4a	0.30 up to 2" thick, incl, 0.33 over 2" up to 4", 0.35 over 4"	± 0.05
Carbon Class 4b	0.18 up to 1" thick, incl 0.22 over 1" up to 2", incl.	± 0.05
Manganese	NONE REQUIRED, HOWEVER IF: < 1.00 > 1.00	± 0.15 ± 0.20
Phosphorus	0.020 **1/**	**4/**
Sulfur	0.010 **1/**	**4/**
Silicon	NONE REQUIRED, HOWEVER IF: < 0.60 > 1.00	± 0.10 ± 0.15 ± 0.20
Chromium	NONE REQUIRED, HOWEVER IF: < 1.25 **3/** > 1.25	± 0.15 ± 0.25
Molybdenum	NONE REQUIRED, HOWEVER IF: < 0.20 3/	
Vanadium	NONE REQUIRED **3/**	± 0.05
Niobium	NONE REQUIRED **3/**	± 0.05
Boron	--- **2/**	**4**
Copper	0.25 **3/**	**4**
Nitrogen	0.03 **3/**	**4**
Titanium, Zirconium, Aluminum, Lead .	0.10 **3/**	**4**
Tin, Antimony, Arsenic.	0.02 **3/**	**4**

1/ Phosphorus and sulfur should be controlled to the lowest attainable levels.

2/ When the amount of Boron is specified in the alloy, its content as determined by heat analysis shall not exceed 0.003 percent.

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

4/ There are no limits on the allowable values for future lots; however, the values may not exceed those listed as the maximum limit.

5/ Values are actual tolerance limits NOT percent tolerances.

6/ Elements not listed in Table, but intentionally added, shall be reported.

Source: MIL-DTL-12560J (MR), 2009.

2.7 MICROSTRUCTURE OF STEEL

The microstructure of pure iron shows clear crystals of iron (ferrite) with their grain boundaries. This metal is very soft and ductile with an ultimate tensile strength if about 300Nmm². As soon as carbon is added to this iron a great change occurs in its structure and properties and the microstructure of a mild steel containing 0.25% to 0.3% carbon. The white constituent is the ferrite, whilst the dark patches represent that part of the structure which contains the carbon. It must be remembered that these patches are not actual carbon but contain it in a chemically combined form. A chemical combination of two elements can be formed in which the final result is totally unlike either of the elements of which the combination is composed. Thus, hydrogen and oxygen combine in a certain proportion to form water (H2O), carbon and oxygen may form carbon monoxide (CO), or carbon dioxide (CO2), and so on. Now iron and carbon unite to form iron carbide (cementite) and they do so in the proportion by weight 1 of carbon to14 of iron. Iron carbide has the chemical formula Fe3C and is a very hard white and brittle substance, so that the more of it the steel contains the harder will it be.

If, now one of the dark portions it will show that the dark, carbon-bearing constituent is in reality a substance built up of alternate light and dark plates. These layers are alternately ferrite (iron) and cementite, and allowing for the great magnification it will be seen how thin the plates are. This substance is called pearlite and is made up of 87% ferrite and 13% cementite. By that there are 100 parts of pearlite contain 13 parts of cementite, and since cementite consist of 1 part of carbon to 14 parts of ferrite (i.e 1 of carbon to 15 of cementite), the 13 parts of cementite in 100 of pearlite will contain 13/15 of carbon = 0.87 or about 0.9. Thus, pearlite contains approximately 0.9% of carbon, and the 0.25% C steel contains 0.25/0.9=28% of pearlite and 72% of ferrite. Pearlite is a strong metal and may be cut reasonably well with cutting tools. It has an ultimate strength of about 770 newtons per square millimeter.

As the carbon content of steel is increased, the proportion of pearlite increases also, until when the steel contains 0.9% of carbon, its structure consists entirely of pearlite. If the carbon content is increased further still there will be some cementite left over and this will appear in the structure as a free constituent left over and this will appear in the structure as a free constituent in the same way as free ferrite appears in the low carbon steels. Now, since ferrite is soft and not very strong, and cementite is hard and brittle but also without much strength, as the carbon (and the pearlite) is increased, the steel will get harder and stronger up to the point when it contains 0.9% of carbon. Beyond this, the cementite is increasing, but not pearlite, so that its hardness will increase but its strength will decrease. This is illustrated in Figure 2.5 which illustrates the effect of carbon content on structure, strength, hardness and ductility.

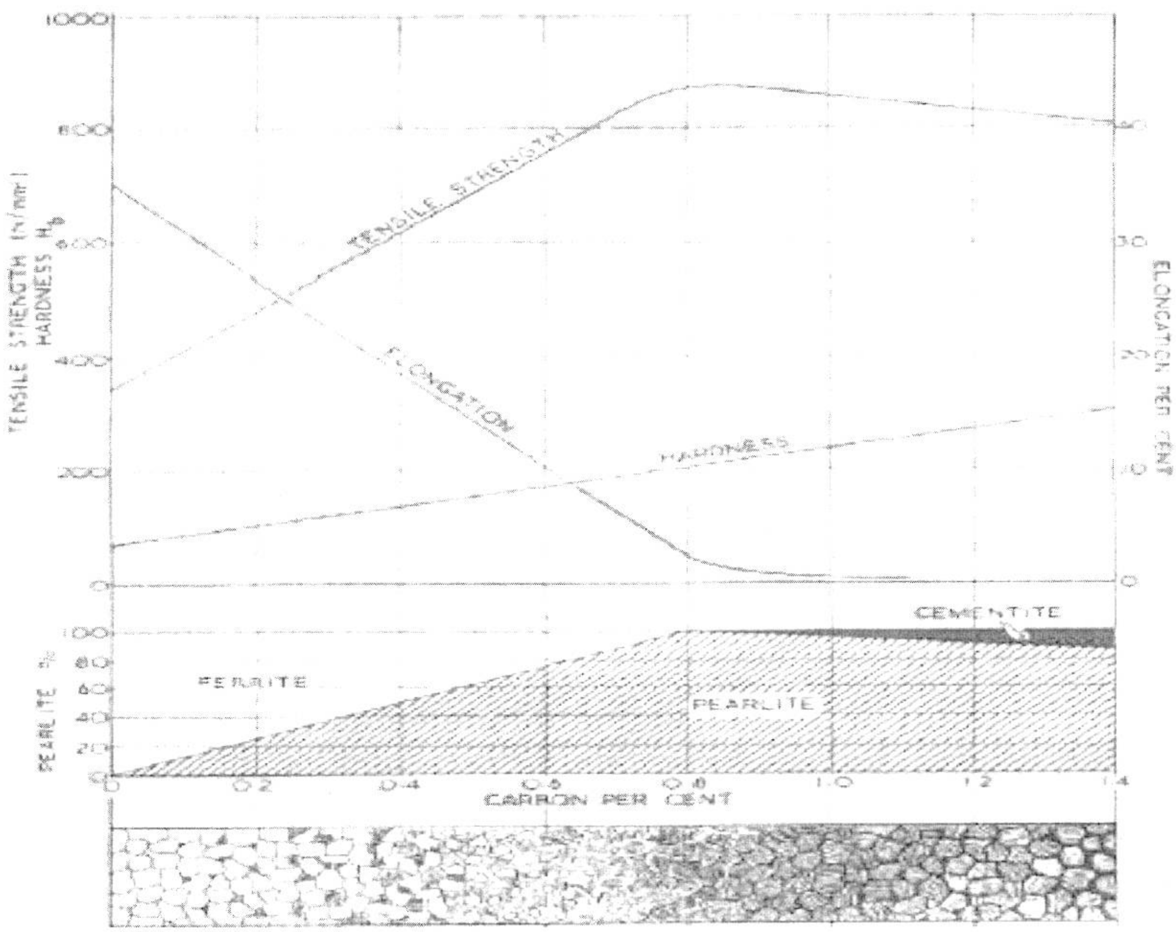


Figure 2.5: The relationship between carbon content, microstructure and mechanical properties of steel. The hardness of a plain carbon steel increases progressively with increase in carbon content. (Durand-charre *et al.*, 2004)

2.8 RELEVANT RESEARCH WORK

Maweja (2005) conducted a research project on optimizing the mechanical properties and microstructure of armored steel plate in the quenched and tempered condition with the aim of developing an improved understanding of the relationship between ballistic properties of martensitic armour plate steels and their structures and mechanical properties. The effect of the chemical composition, austenitisation temperature and tempering temperature on the mechanical properties and on the ballistic performance of martensitic steel armour plates was studied from phase analysis and its quantification by X-ray diffraction, characterization of the martensite using scanning electron microscopy, transmission electron microscopy and atomic force microscopy . It was established in this study that the mechanical properties and the ballistic performance of martensitic steels can be optimized by controlling the chemical composition and the heat treatment parameters.

Garba *et al.*, (2014) conducted a research using Nigerian Steel 65 Mn (NST 65 Mn) as a base material for the development of High Impact Resisting Material. Two new materials, New Material 1 (NM 1) and New Material 2 (NM 2) were developed by increasing the alloy content of manganese, chromium and Nickel in the base material using master alloys. Chemical analysis was carried out according to ASTM E 572-02a (2006) e2. Mechanical Tests were also conducted as specified by ASTM A 370, E 8, E 10, E 18 and E 23using standard samples and equipment. NST 65 Mn Steel was found to have Rockwell Hardness Value of 84.8 HRB, Impact Strength of 70 Joules, and Tensile Strength of 551.6 N/mm^2. NM 1 was found to have Rockwell Hardness Value of 125 HRB, Impact Strength of 111 Joules, and Tensile Strength of 1,744 N/mm^2. NM 2 was found to have Rockwell Hardness Value of 114 HRB, Impact Strength of 73 Joules, and Tensile Strength of 1,317 N/mm^2. The mechanical tests conducted on Armoured Tank Panel (ATP) in previous research revealed that it has Rockwell Hardness Value of 117 HRB, Impact Strength of 109 Joules, and Tensile Strength of 1,420 N/mm^2. The results showed that the NM 1is better in mechanical properties than NST 65 Mn Steel, NM 2 and ATP. The New Material 2 is better than NST 65 Mn steel but less than the ATP. The results established that New Material 1 can be used as a material for High Impact Resistance and therefore the potentials of NST 65 Mn Steel as base material is high.

Experimental Research on New Grade of Steel Protective Material for Light Armoured Vehicles was done by Bernetič *et al.*, (2012). An investigation of new PROTAC 500 armour steel was conducted. Three plates were heat treated to different states. One was quenched, the second and third were quenched and low temperature tempered at 220 and 280 °C for 3 hours. A tensile test, hardness measurements, and an instrumented Charpy test were performed. Metallographic examination was performed by optical microscopy (OM). Ballistic resistances of all three steel plates were measured. The behavior of steel was tested using armour piercing projectiles 7.62×39 mm API BZ (former soviet designation for Armor Piercing Incendiary bullet). The best results were obtained in quenched state.

Karagoz *et al.*, (2008) researched on a fractographical Study on Boron added armour steel developed by alloying and heat treatment to understand its ballistic performance. In this study newly developed boron added armour steel has been rolled to form sheet product. Heat treatment series including austenitization, quenching and then tempering have been applied on boron added armour steel respectively. The effects of formed microstructures on mechanical properties have been studied extensively. Furthermore failure mechanism has been determined through fractographical examinations by using scanning electronic microscopy (SEM). The study shows that ductile fracture develops as a function of high toughness and material will resist to impact, On the other hand, brittle fracture is a function of high hardness and material will not outstand to kinetic impact by projectile. The experimental steel shows a good combination of hardness and toughness and with further development work a good armour steel could be developed.

Fadare et *al.*, (2011) studied the effect of heat treatment (annealing, normalizing, hardening, and tempering) on the microstructure and some selected mechanical properties of NST 37-2 steel were studied. Sample of steel was purchased from local market and the spectrometry analysis was carried out. The steel samples were heat treated in an electric furnace at different temperature levels and holding times; and then cooled in different media. The mechanical properties (tensile yield strength, ultimate tensile strength, Young's modulus, percentage reduction, percentage elongation, toughness and hardness) of the treated and untreated samples were determined using standard methods and the microstructure of the samples was examined using metallographic microscope equipped with camera. Results showed that the mechanical properties of NST 37-2 steel can be changed and improved by various heat treatments for a particular application. It was also found that the annealed samples with mainly ferrite structure gave the lowest tensile strength and hardness value and highest ductility and toughness value while hardened sample which comprise martensite gave the highest tensile strength and hardness value and lowest ductility and toughness value.

Sanusi *et al.*, (2015) conducted a research on the ballistic performance of a quenched and tempered steel. Low alloy steel was selected where austenization, quenching and finally tempering at 600°C were applied to it. Thereafter, the heat-treated steel was shot with armour piercing 7.62 mm calibre and the occurrence of failure, after the interaction between the projectile and the steel, was investigated. The shot was performed at zero degree (0°) obliquity with a projectile velocity of 830m/s. After the shot, microstructural and fractographical examinations were carried out on the sample taken from the perforated region using scanning electron microscopes to determine the matrix phase and secondary phases. It was observed that the steels had tempered martensitic-bainitic matrices after heat treatments; a crater was formed on the front side of the steel; deformed and transformed adiabatic shear bands had an effect on the crack formation and propagation in the matrix; and perforation mode of the steels was typical petalling.

In this study, occurrence of failure after the interaction between an armour piercing 7.62 mm caliber projectile and a tempered bainitic steel has been investigated by Atapek *et al.,* (2001). The shot was performed at zero degree with a projectile velocity of 840 m/s. After the shot, microstructural and fractographical examinations were carried out on the sample taken from the perforated region. In the etched sample, it was observed that the morphology of the original microstructure had changed and adiabatic shear bands (ASBs) were formed in regions close to the direction of penetration. Main failure is ductile (plastic) deformation was followed by cleavage after shot. Cracks due to adiabatic shear band and formation of abrasive wear were seen. The perforation mode of the steel was a typical petalling.

Ballistic testing is a vital part of the armor design. However, it is impossible to test every condition and it is necessary to limit the number of tests to cut huge costs. With the introduction of hydrocodes and high performance computers; there is an increasing interest on simulation studies to cutoff these aforementioned costs. Tansel (2010) studied the numerical modeling of ballistic impact phenomena, regarding the ballistic penetration of hardened steel plates by 7.62 mm AP (Armor Piercing) projectile. Penetration processes of AP projectiles are reviewed. Then, a survey on analytical models is given. After the introduction of fundamentals of numerical analysis, an intensive numerical study is conducted in 2D and 3D. Johnson Cook strength models for the four different heat treatments of AISI 4340 steel were constructed based on the dynamic material data taken from the literature. It was found that 2D numerical simulations gave plausible results in terms of residual projectile velocities, considering the literature review. Then, 3D numerical simulations were performed based on the material properties that were selected in 2D studies. Good agreement was obtained between the numerical and test results in terms of residual projectile velocities and ballistic limit thicknesses. It was seen that the ballistic protection efficiency of the armor plates increases with the increasing hardness, in the examined range.

Light microscopy, scanning electron microscopy, and transmission electron microscopy were employed to examine the microstructural basis for the mechanical properties of as-quenched and tempered (High strength, low alloy) HSLA-100 steel conducted by Victor (1990). Examination of the alloy revealed granular bainite with martensite and retained austenite in the as-quenched state which upon aging at temperatures below the lower transformation temperature, 677°C, formed tempered bainite with precipitates of copper and carbides. These results indicate the strength and toughness of HSLA-100 steel aged below 677°C is based primarily on the fine prior austenite grain size and classic copper precipitation behavior but also on the bainitic dislocation substructure and carbides. After tempering at 677°C, HSLA-100 steel has a dual-phase microstructure consisting of bainitic ferrite laths, fine ferrite grain clusters and martensite with precipitates of carbides and overaged copper. The results indicate the yield strength of the overaged alloy is based on the fine ferrite grain and bainite lath sizes, the fine carbide distribution and elastic moduli strengthening while the toughness is the result of the high-angle ferrite grain boundaries, the fine intralath carbides and the ductile overaged copper precipitates.

2.9 BRIEF SUMMARY OF THE RELEVANT RESEARCH

It can be established from these relevant researches that the mechanical properties and the ballistic performance of armour steels can be optimized by controlling the chemical composition and the heat treatment parameters, an armour steel with increased values of mechanical properties (Impact strength, hardness, tensile strength) and necessary chemical composition would deliver better results of ballistic properties which can be determined by conducting mechanical tests, chemical and microstructural analysis which is the objective of this project.

2.10 STEEL INDUSTRY IN NIGERIA

The steel industry is a very important sector in the nation's economy which produces items such as iron rods, barb wires, coils, as well as metal doors and windows, while it forms the bedrock of the country's industrialisation. The sector also provides employment to millions of Nigerians, particularly in steel rolling companies which produce steel materials. There are more than 15 functioning steel rolling mills producing reinforced bars; about three functioning cold rolled steel mills producing cold rolled flat sheets; and about three producing or about to commence the production of wire coils which sums up to a total functional steel mills of 21 in the country (Abdullahi, Y. 2014)

Breakdown steel industry in Nigeria - 13 rolling mills, 7 mini mills and 2 integrated steel companies in the country (Ezeemon, V. 2015):

1. South-East: Onitsha (Allied Steel Co.), Owerri (Metcombe Steel Co.) and Enugu (Nigersteel Co.),

2. South-South: Aladja-Ovwian (Delta Steel Co.,), Asaba (General Steel Mill,) and Eket (Qua Steel Products)

3. North-Central: Ajaokuta (Ajaokuta Steel Co. Ltd.), Ilorin (Union Steel Co. and Commercial, Metal & Chemical Industries) and Jos (Jos Steel Rolling Company)

4. North-West: Kano (Nigerian Spanish Eng. Co.,) and Katsina (Katsina Steel Rolling Co)

5. Abuja: (Baoyao Futurelex))

6. South-West, Ikeja (Asiastic Manarin Ind, Continental Iron & Steel Co. and Universal Steel Co,), Ikorodu (Kew Metal Industries, and Mayor Eng. Co.,) Otta (Federated Steel Industry, Selsametal), Ibadan (Alliance Steel Co.) and Oshogbo (Oshogbo Steel Co).

Over the years, the steel industry in Nigeria has been facing some harrowing challenges that inhibit its growth which includes erratic power supply and importation of raw materials (Mobolaji, A., 2015)

CHAPTER THREE

3.0 METHODOLOGY

3.1 MATERIAL

The steel plate tested for this project is as-received armour steel with a thickness of 6mm and a dimension of 300mm by 500mm. It was sourced from the Research and Development Centre, Defense Industries Corporation of Nigeria, Kaduna, Nigeria.

3.2 EQUIPMENT

The details about various equipment and machines used during this project are shown in Table3.1.

3.3 EXPERIMENTAL PROCEDURES

3.3.1 CHEMICAL COMPOSITION ANALYSIS

Chemical analysis of the plate was conducted in accordance with the applicable method specified in ASTM A751 (U.S Military Specification, 2006) to determine the specific elemental constituents of an alloy by showing the exact percentage of each element present in the test sample using a ARL™ 24770Thermo fisher quantodesk spectrometer available at the University of Lagos, Nigeria. Firstly the steel armour plate was cut into a small sample (15mm x15mm) with a cutting wheel made up of silicon carbide abrasives and mounted with compressive molds. The sample was then polished with an aluminium carbide abrasive of 120ɥm down to 50ɥm and it was cleaned with acetone followed by ethanol to acquire a smoother surface. The sample was then etched to reveal microstructural features of the armour steel. The sample is later fed into the Optical Emission Spectroscopy machine which operates by heating the surface of the armour steel sample until it emits light. The emitted light is collected and then dispersed via prism. The resultant spectrum reveals the presence of specific elements by their characteristic wavelengths. The intensity of the elemental wavelength is measured to determine the ratio of the element to the rest of the alloy. The Spark-DAT analysis alone takes around 22 s for a single measurement including 2 seconds Argon flush. The analysis was compared with the declared composition established in accordance with the requirements of MIL-DTL-46100E shown in Table 4.1.

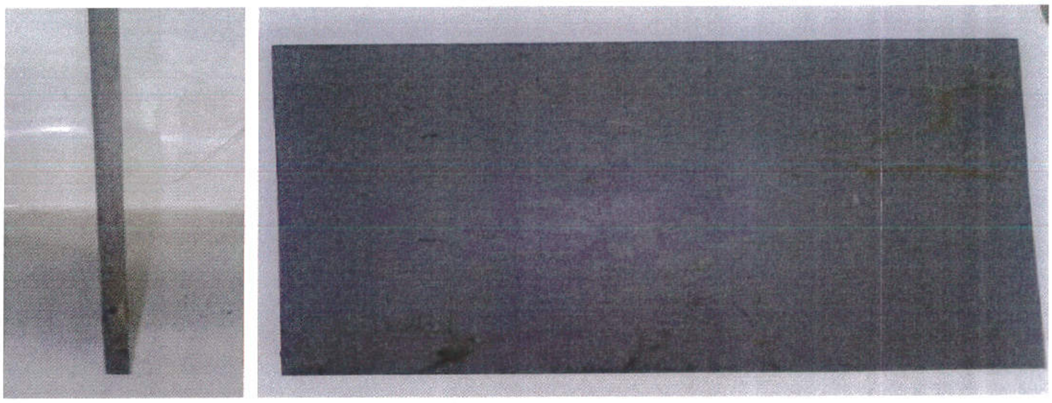


Plate 3.1: The armour steel plate side view (left) and front view (right)

Plate 3.2: Cutting operation

Plate 3.3: The armour steel sample preparation

Table: 3.1: Details of testing equipment/machines used

MACHINE	MODEL NO.	DESCRIPTION	MANUFACTURE/ DATE	COUNTRY	CENTER OF RESIDENCE
Universal testing machine	Instron 3369	Load:50 N (11,250 lbf) capacity, Maximum speed 500 mm/min (20 in/min), 1193 mm (47 in) vertical test space	Instron, 2008	North America	(EMDI), AKURE
Charpy impact testing machine		360 Joules capacity	Atico advanced technology inc. 2012.	India	ABUAD, ADO-EKITI, EKITI STATE.
Optical Microscope	ME600	Magnification at full screen to 1000x, Numerical aperture 0.13-0.9, working distance 10.0-0.39.	Nikon eclipse, 2005.	Melville, NY, U.S.A.	EMDI, AKURE
Micro Hardness testing machine	LM700A	Diamond Indenter, Vertical: 3", Throat 3.25", Load Selection 10, 25, 50, 100, 200, 300, 500, 1000, Load Duration Timer, 10x Filar Eyepiece, Certified to ASTM Specifications,	LECO Cooperation, April, 2005.	Lakeview Ave Saint Joseph, MI, USA.	EMDI, AKURE
Thermo fisher quatodesk spectrometer	ARL™ 24770	Wavelength 170-410 nm, Ambient temperature 15-30°C, 110/230V. 50/60 Hz.	Thermo fisher, 2008.	Waltham, MA USA.	UNILAG, LAGOS.

Figure 3.3: An ARL™ 24770 Thermo fisher quantodesk spectrometer machine.

3.3.2 MICROSTRUCTURAL ANALYSIS

The microstructural characteristics of the armour steel was analyzed using a ME600 Nikon eclipse optical microscope available at the Engineering materials development institute, Akure in accordance with ASTM A751. Proper preparation of the armour steel specimen was perform to determine microstructure and content. Various step-by-step process were followed in sequence, the steps included cutting, mounting, course grinding, fine grinding, polishing, etching and microscopic examination. During cutting was performed using a cutting machine meanwhile, molding process was carried out to facilitate handling of the specimen during grinding, polishing and etching process.

Grinding process was carried out in order to maintain the flatness of the sample at successive sessions with 320, 600, 1000 mesh size SiC abrasive. During polishing process, edge rounding need to be avoid by select an appropriate preparation sequence and also the removal of deformation need to be ensure in order to reveal the true structure. Etching was carried out with nital (3% of HNO3) to reveal its microstructural features. The optical microscope was then used to study the microstructure.

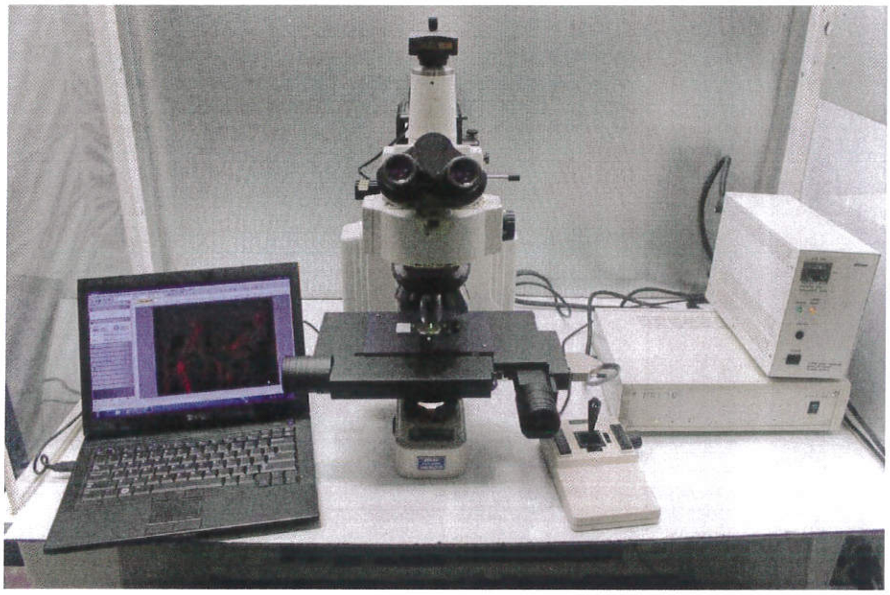


Figure 3.4: An ME600 Nikon eclipse optical micrometer.

Figure 3.5: Microstructural specimen of the amour steel.

3.3.3. MECHANICAL CHARACTERISATION OF THE ARMOUR STEEL

According to ISCOR *et al.,* (2003) the hardness of the steel; the tensile strength; the elongation during tensile testing at room temperature; and the Charpy impact energy at – 40°C are the mechanical tests required for predicting the properties of steel to be used for high impact performance.

Therefore, the following mechanical tests are to be conducted on the material based on ASTM codes are:

I. Hardness test (ASTM E10, ASTM E18)

II. Tensile test (ASTM E8)

III. Impact test ASTM (E23, ASTM A370).

3.3.3.1 HARDNESS TEST

Hardness is generally considered as resistance to penetration. The harder the materials, the greater the resistance to penetration. Hardness is directly related to the mechanical properties of the material. Factors influencing hardness include microstructure, grain size, strain hardening, etc. Generally as hardness increases so does yield strength and ultimate tensile strength (UTS). A LM700A Micro Hardness testing machine manufactured by LECO Corporation was used for this project in accordance with ASTM E10 standard requirement for hardness test.

The Vickers method is based on an optical measurement system. The Micro hardness test procedure, ASTM E-384, specifies a range of light loads using a diamond indenter to make an indentation which is measured and converted to a hardness value. A square base pyramid shaped diamond is used for testing in the Vickers scale.

Firstly the armour steel sample was prepared and mounted in a plastic medium in order to provide a small enough specimen that can fit into the tester, to make the specimen's surface smooth to permit a regular indentation shape and good measurement, and to ensure the sample can be held perpendicular to the indenter. The armour steel sample was indented with the micro hardness testing machine with a load of 490MN at 10 seconds repeatedly for three successive sessions and the average reading was determined.

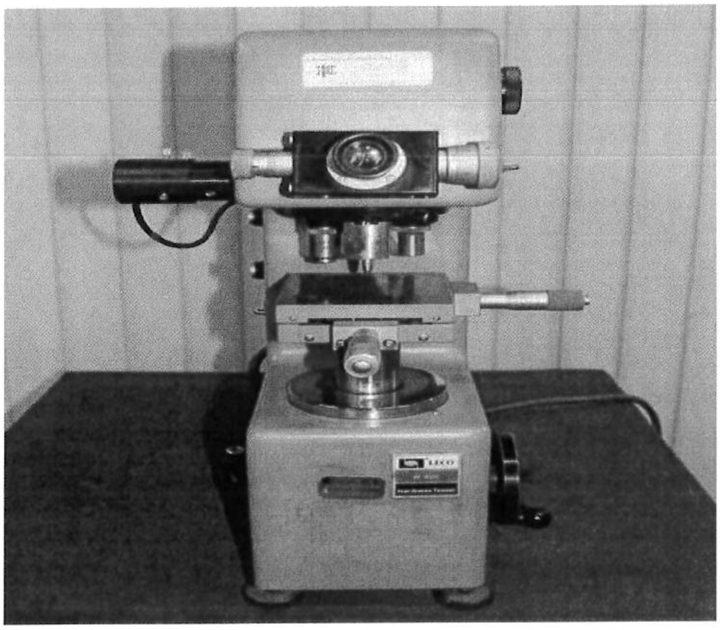


Figure 3.6: A LM700A Micro Hardness testing machine.

3.3.3.2 TENSILE TEST

The tensile test is a method to measure the mechanical properties of materials. It relates the effect of a uniaxial tensile load (force) on the elongation (change in length) of a standard specimen. From knowledge of the specimen geometry the engineering stress and strain from the load vs. elongation data can be determined. Engineering stress (σ_E) is equal to the force (F) per unit area based on the original cross-sectional area (Ao) of the sample and does not take into account that this cross-section decreases as the test progresses.

The armour steel sample was measured and machined into a standard required dimension used for tensile test, two indentations were placed on using marking jig and hammer in the narrow section of the specimen, centered, spaced exactly two inches apart then the armour sample was loaded into the 3369 Instron Universal Testing Machine, tightened grips. Extensometer was mounted to the center of the specimen then the machine was started and graph o elastic range was noted until extensometer would go no further. The machine was stopped, extensometer detached, and chart speed set to1 inch/min. Extensometer was then reset, continued experiment until fracture. After fracture, the specimen was removed and final length measured with cross sectional area of the fractured armour steel sample. Result data (Tensile stress, tensile strain, elongation, modulus and so on) are acquired from the monitor and are used for analysis and computed to an ECXEL.

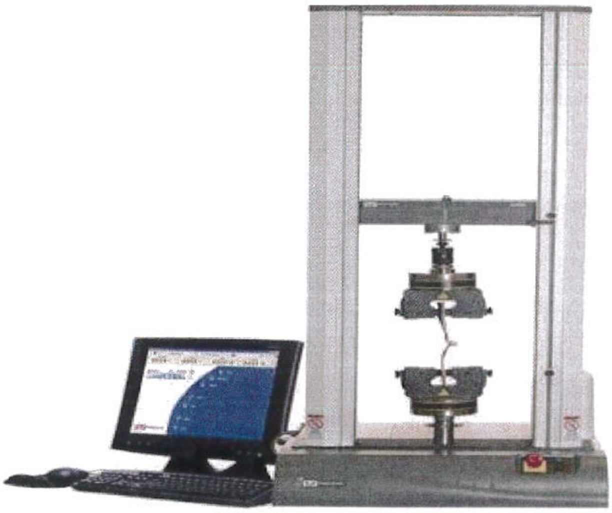


Figure 3.7: A 3369 Instron Universal Testing Machine

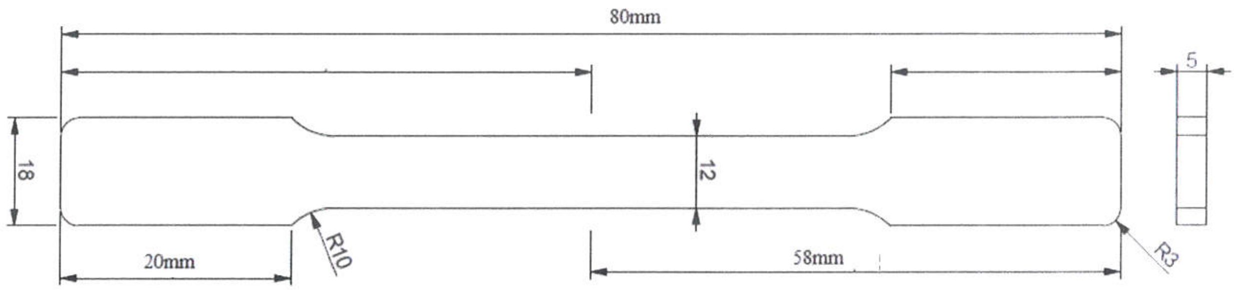


Figure 3.8: The armour steel tensile specimen dimension

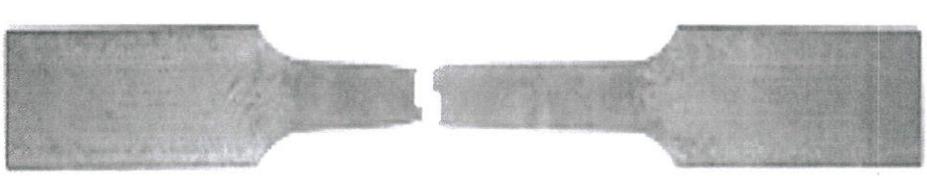


Figure 3.9: Armour steel tensile specimen post-fracture

3.3.3.3 IMPACT TEST

Charpy impact testing involves striking a standard notched specimen with a controlled weight pendulum swung from a set height. The standard Charpy-V notch specimen is 55mm long, 10mm square and has a 2mm deep notch with a tip radius of 0.25mm machined on one face. The specimen was supported at its two ends on an anvil and struck on the opposite face to the notch by the pendulum. The amount of energy absorbed in fracturing the test-piece was measured and this gives an indication of the notch toughness of the test material. The pendulum swings through during the test, the height of the swing being a measure of the amount of energy absorbed in fracturing the armour steel.

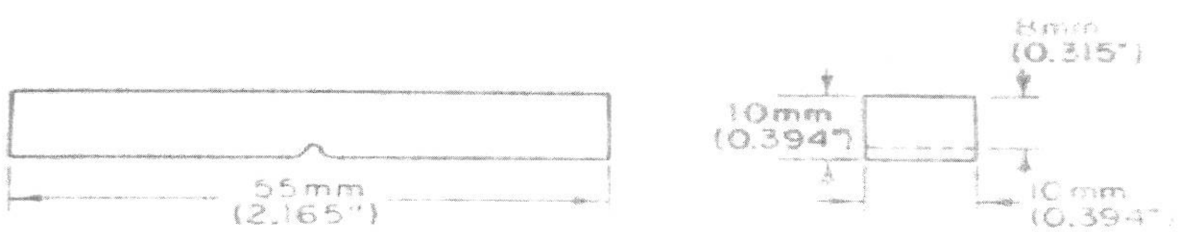


Figure 3.10: The armour steel impact test specimen

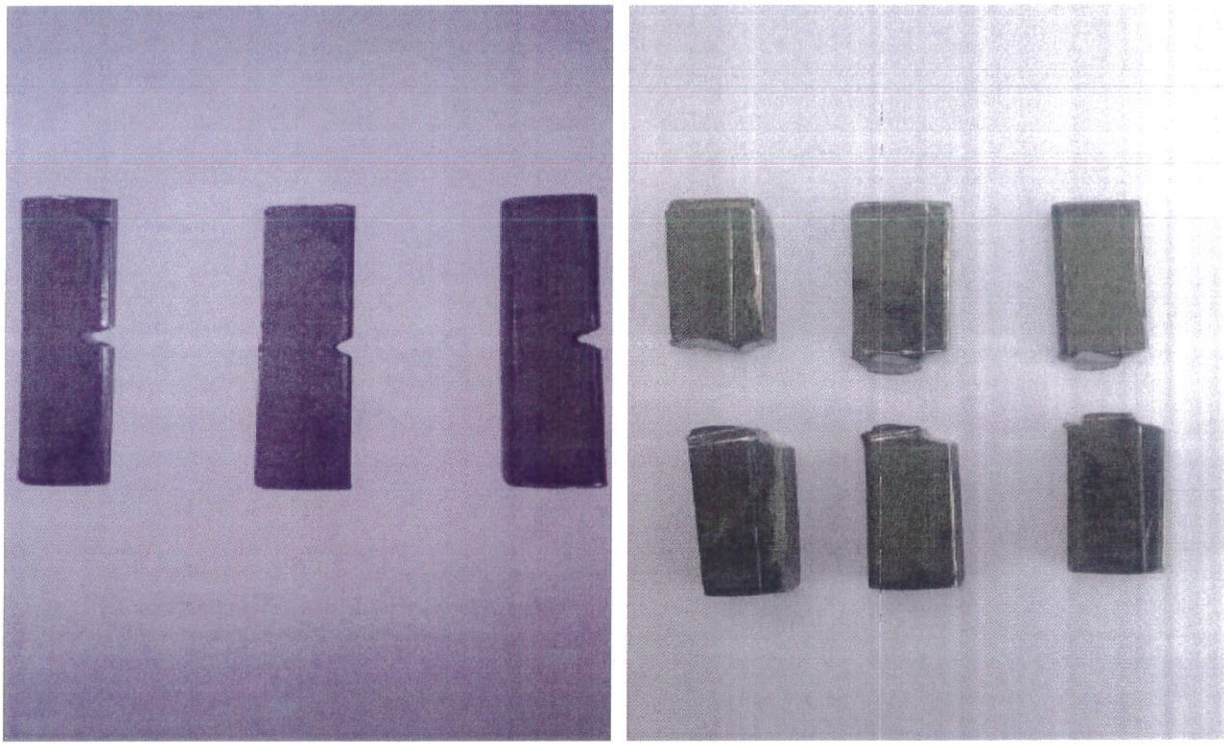


Figure 3.11: The armour steel specimen before (left) and after fracture (right).

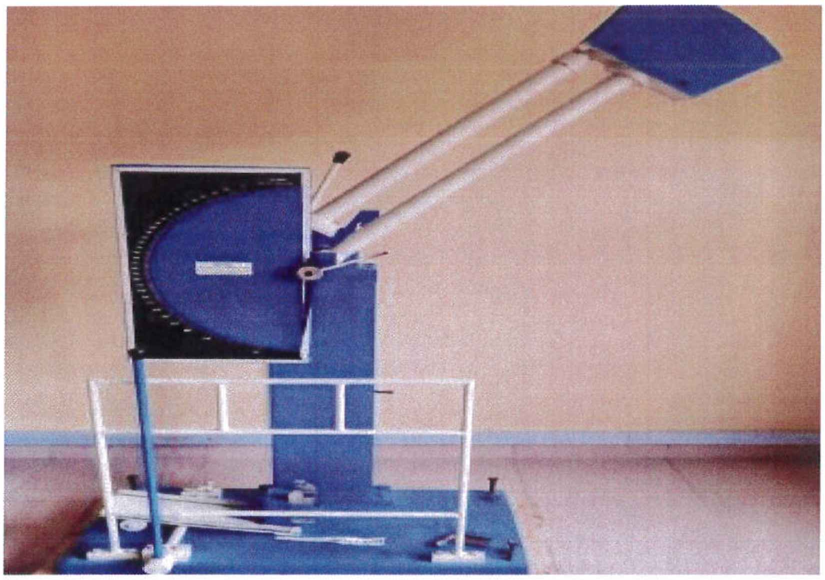


Figure 3.12: The Charpy impact testing machine

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 RESULT OF THE CHEMICAL COMPOSITION ANALYSIS

The result of the chemical composition test shown in Table 4.1 which indicates the specific elemental constituents and the exact percentage of each element present in the armour steel test sample.

Table 4.1: Result of the chemical composition analysis

ELEMENTS	Fe (%)	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)
Avg.	96.78	0.2500	0.1672	0.5648	<0.002	<0.005	<0.932	0.6581

ELEMENTS	Mo (%)	Cu (%)	Ti (%)	Nb (%)	Co (%)	V (%)	W (%)
Avg.	0.3482	0.1935	<0.000	<0.000	<0.000	<0.001	0.1738

4.2 Comparison of the Armour Steel Sample Chemical Composition to MIL-DTL-12560J and with other presently available Armour Steel

The armour steel sample chemical composition was compared to military standard (MIL-DTL-12560J) and with other presently available armour steel (RAMOR 550, NST 65Mn, PROTAC 500 and HSLA-100) used for high impact performance, it showed reasonable similarities in accordance within permissible limits for required chemical composition of armour steel as shown in Table 4.2.

Table 4.2: shows the comparison of the armour steel chemical properties Defense standard, and other available armour steel (RAMOR 550, NST 65Mn, PROTAC 500 and HSLA-100)

ELEMENTS	**1** MIL-DTL-12560J	**2** RAMOR 550	**3** NST 65Mn	**4** PROTAC 500 steel	**5** HSLA-100 STEEL	STEEL SAMPLE
Carbon	0.18-0.35	0.36	0.30	0.30	0.06	0.2500
Manganese	<1.00->1.00	1.00	1.04	1.20	0.75-1.05	0.5648
Nitrogen	0.03	2.50	0.01	0.70	3.35-3.65	0.6581
Chromium	< 1.25 > 1.25	1.50	0.01	0.80	0.45-0.75	<0.932
Sulphur	0.010	0.005	0.015	-	0.006	<0.005
Phosphorus	0.020	0.015	0.005	-	0.020	<0.002
Iron		-	97.78	-	-	96.78
Vanadium	NONE REQUIRED	-	0.10	-	-	<0.001
Silicon	< 0.60 > 0.60 to < 1.00 > 1.00	0.60	0.02	0.70	0.40	0.1672
Copper	0.25	-	0.02	-	1.45-1.75	0.1935
Molybdenum	< 0.20 > 0.20	0.80	0.70	0.35	0.55-0.65	0.3482
Boron		0.005	-	-	-	-
Niobium	NONE REQUIRED	-	-	-	0.02-0.06	<0.00
W		-	-	-	-	0.1738

1 MIL-DTL-12560J (Military Defence Standard, 2009)

2 RAMOR 550 (Villacero Company hand book, 2015)

3 NST 65Mn- Nigerian Steel 65 Manganese (Garba, K. *et al.*, 2013)

4 PROTAC 500 steel (Bernetič, J. *et al.*, 2012)

4.3 RESULT OF THE MICROSTRUCTURAL ANALYSIS

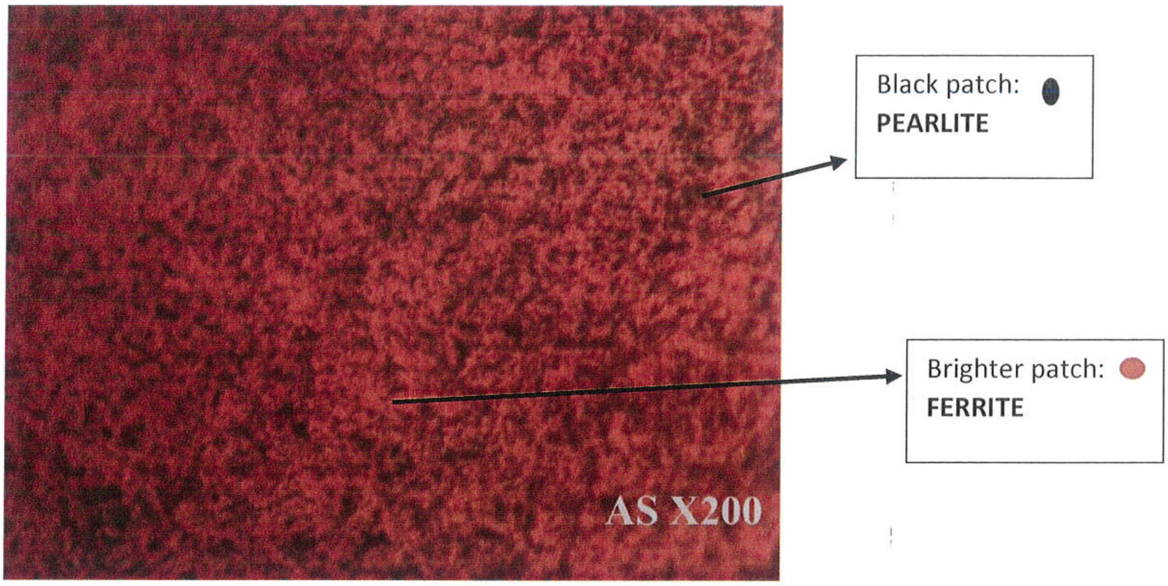


Figure 4.1: The micrograph of the armour steel

The microstructure of this steel is a fine and homogeneous bianitic matrix throughout the cross section of the armour plate. This fine microstructure explains the high hardness of the armour steel. The white constituent is the ferrite, whilst the dark patches represent that part of the structure which contains the Pearlite while comprises of 87% ferrite and 13% Iron carbide. Pearlite contains approximately 0.9% of the carbon, which contains 0.25/0.9=28% of pearlite and 72% of ferrite. The micrograph shows the presence of Ferrite and Pealite in a tempered Bianitic matrix. Bianite is a plate-like microstructure or phase morphology that forms in steels at temperature of 250°C-550°C depending on the alloy content (Hoenycomb *et al.*, 2000). Bainitic steels are known to exhibit high strength and hardness and also a high level of toughness, for a microstructure consisting of fine bainite, strength follows. The general definition of bainite is that the microstructure consists of a non-lamellar mixture of ferrite and iron carbides (Chris, et al., 2015). The high concentration of dislocations in the ferrite present in bianite makes this ferrite harder than it normally would be (Durand-charre *et al.*, 2004). Bianite is an intermediate of pearlite and martensite in terms of hardness. For this reason, the bianitic microstructure becomes useful in that no additional heat treatments are required after initial cooling to achieve a hardness value between that of pearlitic and martensitic steels.

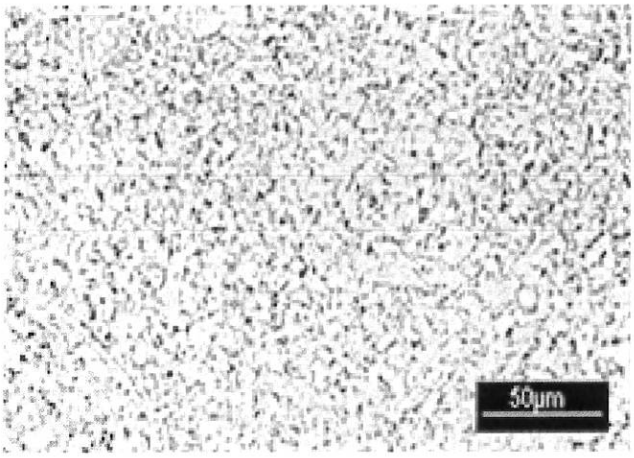


Figure 4.2: Ferrite-pearlite microstructure of a typical HSLA structural steel at 50ɥm magnification. (Durand-charre *et al.*, 2004)

4.4 RESULT OF THE MECHANICAL TEST

4.4.1 HARDNESS RESULT

The hardness test was performed three times to derive accurate result as shown in Table 4.3 in Vickers and Rockwell hardness scale but making use the hardness conversion chart in (Appendix A) the approximate Brinell hardness conversion number is 479BHN.

Table 4.3: Hardness test result of the armour steel sample

S/N	LABEL	READING 1		READING 2		READING 3		AVERAGE	
	HARDNESS SCALE	HV	HR	HV	HR	HV	HR	HV	HR
1	ARMOUR STEEL SAMPLE	507.4	49.7	511.4	49.8	511.2	49.9	**510.0**	**49.8**

4.4.2 TENSILE RESULT

The tensile result of the armour test is shown in Table 4.4, and Figure 4.3 showing the stress/strain graph of the armour steel.

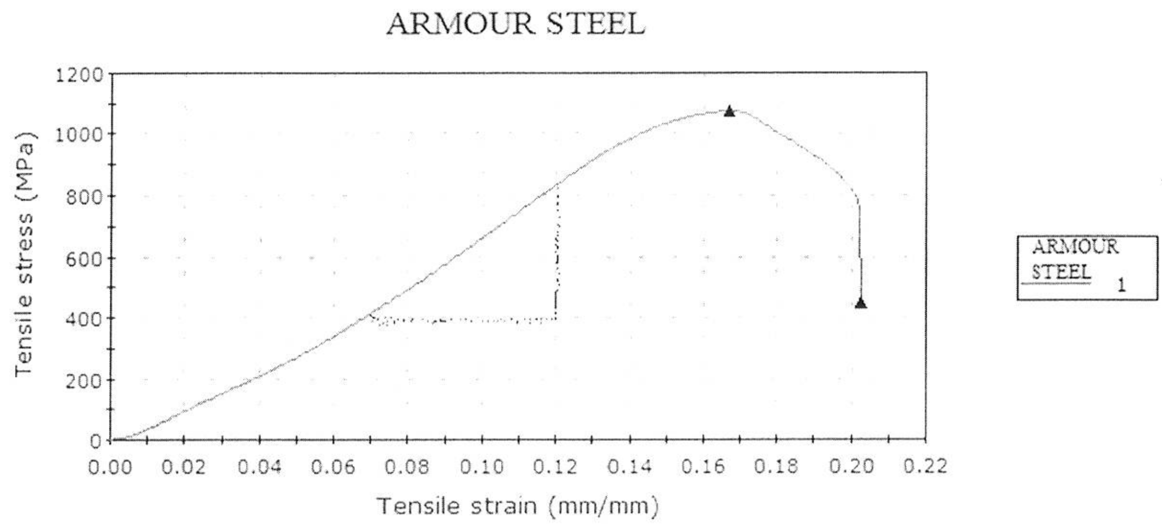


Figure 4.3: The stress/strain graph of the armour steel

Calculations:

Young's modulus of elasticity. $E = \frac{\text{Change in Stress } \sigma}{\text{Change in Strain } \varepsilon} = \frac{810-400}{0.12-0.07} =$ **8200Pa**

Ultimate tensile strength $= \frac{\text{Maximum load}}{\text{Original cross sectional area}} = \frac{619{,}680\text{N}}{0.00048\text{m}^2} =$ **1291MPa**

Percentage elongation $= \frac{\text{increase in length}}{\text{Original length}} \times 100 = \frac{94.5-85}{85} \times 100 =$ **11%**

Table 4.4: Showing the tensile result of the armour steel

	Area (m^2)	Length (mm)	Width (mm)	Modulus (Automatic) (MPa)
1	0.00048	85.00000	12.00000	8603.61694

	Energy at Yield (Zero Slope) (J)	Load at Yield (Zero Slope) (N)	Tensile stress at Yield (Zero Slope) (MPa)	Tensile strain at Yield (Zero Slope) (mm/mm)
1	368.71364	515598.00	1074.04297	9.26706

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile stress at Break (Standard) (MPa)	Tensile extension at Break (Standard) (mm)
1	596238.00	9.25238	748.95050	17.20218

	Tensile extension at Yield (Zero Slope) (mm)	Tensile strain at Maximum Tensile extension (mm/mm)	Tensile stress at Maximum Tensile extension (MPa)	Load at Maximum Tensile extension (N)
1	14.19984	9.35000	447.63815	619680.00

4.4.3 IMPACT RESULT

The Charpy impact v notch test was perform four time to derive accurate results at 40°c and the average result was recorded as shown in Table 4.5, the armour steel sample provided an impact resistance of 27.1Joules.

Table 4.5: Impact test result of the armour steel sample

TEST 1 (Joules)	TEST 2 (Joules)	TEST 3 (Joules)	TEST 4 (Joules)	AVERAGE (Joules)
28	26.7	27	26.9	**27.15**

4.5 COMPARISON OF MECHANICAL PROPERTY

The mechanical properties of the armour steel was compared to MIL-DTL-12560J and other available armour steel as shown in Table 4.6. The armour steel showed reasonable similarities in accordance within the standard permissible limits of required mechanical properties for high impact performance.

Table 4.6: Comparison of the armour steel mechanical properties to MIL-DTL-12560J and other available armour steel.

MECHANICAL PROPERTY	MIL-DTL-12560J.	RAMOR 550	NST 65Mn	PROTAC 500	ARMOUR STEEL SAMPLE
Hardness(BHN)	262-655	540-600	460	525	479
UTS (MPa)	895-2400	1,850	-	1,762	1,291
Elongation (%) Min.	6-16	7	-	11.6	11
Charpy (J) "V" Notch Min -40°C	5-40	16	70 At -45°C	-	27.15
Nominal Thickness mm	3-160	10	-	10	6

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The chemical composition, microstructure, mechanical properties of the armour steel sample have been determined and compared to MIL-DTL-12560J (Military standard) and with other presently available armour steel. Chemical analysis showed the elemental constituents and the exact weight per percentage of each element present in the test sample. Microstructural analysis was carried out on etched sample of the plate which exhibited the desired bainitic microstructure. Dispersed within the bainitic microstructure were high carbon micro constituents consisting of iron carbides and pearlite. Then hardness, tensile and impact strength of the plate were assessed following standard procedures. The results showed that the specimen tested has a tensile strength of 1291MPa, a hardness value of 479BHN, 11% elongation, and impact resistance of 27.15J. The mechanical performance of the plate was in consonance with the minimum mechanical requirements of MIL-DTL-12560J standards. This study, therefore established that the tested armour steel plate is effective for high impact performance.

5.2 RECOMMENDATION FOR FUTURE RESEARCH

I recommend that a ballistic experimental analysis of the armour steel plate be conducted and subjected to a high velocity of 0.30 calibre armour piercing projectile, this would provide a better understanding of the ballistic properties of the armour steel.

I recommend that a better microstructural study be conducted using a scanning electron microscope (SEM) to better aid investigation on the microstructural study of the armour steel.

I recommend a fractures analysis be conducted on the post fractured specimen of the armour steel after impact test.

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APENDIX A

Hardness Conversion Chart

Approximate equivalent hardness numbers for carbon and alloy steels

Rockwell				Rockwell Superficial			Brinell	Vickers	Knoop	Scleroscope	Approx. Tensile Strength of Steel (PSI)
A Scale 60kg Diam. Brale	B Scale 100kg 1/16" Ball	C Scale 150kg Diam. Brale	D Scale 100kg Diam. Brale	15N Scale 15kg Diam. Brale	30N Scale 30kg Diam. Brale	45N Scale 45kg Diam. Brale	3000kg 10 mm Ball		500g or Greater Load		
92	-	80.0	87	97	92	87	-	1865	-	-	-
92	-	79.0	86	-	92	87	-	1787	-	-	-
91	-	78.0	85	96	91	86	-	1710	-	-	-
91	-	77.0	84	-	91	85	-	1633	-	-	-
90	-	76.0	83	96	90	84	-	1556	-	-	-
90	-	75.0	83	-	89	83	-	1478	-	-	-
89	-	74.0	82	95	89	82	-	1400	-	-	-
89	-	73.0	81	-	88	81	-	1323	-	-	-
88	-	72.0	80	95	87	80	-	1245	-	-	-
87	-	71.0	80	-	87	79	-	1160	-	-	-
87	-	70.0	79	94	86	78	-	1076	-	99	-
86	-	69.0	78	-	85	77	-	1004	-	98	-
85.6	-	68.0	76.9	93.2	84.4	75.4	-	940	920	97	-
85.3	-	67.5	76.5	93.0	84.0	74.8	-	920	908	96	-
85.0	-	67.0	76.1	92.9	83.6	74.2	-	900	895	95	-
84.7	-	66.4	75.7	92.7	83.1	73.6	-	880	882	93	-
84.4	-	65.9	75.3	92.5	82.7	73.1	-	860	867	92	-
84.1	-	65.3	74.8	92.3	82.2	72.2	-	840	852	91	-
83.8	-	64.7	74.3	92.1	81.7	71.8	745*	820	837	90	-
83.4	-	64.0	73.8	91.8	81.1	71.0	-	800	822	88	-
83.0	-	63.3	73.3	91.5	80.4	70.2	-	780	806	87	-
82.6	-	62.5	72.6	91.2	79.7	69.4	710*	760	788	86	-
82.2	-	61.8	72.1	91.0	79.1	68.6	-	740	772	84	-
81.8	-	61.0	71.5	90.7	78.4	67.7	-	720	754	83	-
81.3	-	60.1	70.8	90.3	77.6	66.7	653*	700	735	81	-
81.1	-	59.7	70.5	90.1	77.2	66.2	-	690	725	-	-
80.8	-	59.2	70.1	89.8	76.8	65.7	-	680	716	80	329,000
80.6	-	58.8	69.8	89.7	76.4	65.3	-	670	706	-	324,000
80.3	-	58.3	69.4	89.5	75.9	64.7	620*	660	697	79	-
80.0	-	57.8	69.0	89.2	75.5	64.1	611*	650	687	78	-
79.8	-	57.3	68.7	89.0	75.1	63.5	601*	640	677	77	309,000

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Approximate equivalent hardness numbers for carbon and alloy steels

Rockwell				Rockwell Superficial			Brinell	Vickers	Knoop	Scleroscope	Approx. Tensile Strength of Steel (PSI)
A Scale 60kg Diam. Brale	B Scale 100kg 1/16" Ball	C Scale 150kg Diam. Brale	D Scale 100kg Diam. Brale	15N Scale 15kg Diam. Brale	30N Scale 30kg Diam. Brale	45N Scale 45kg Diam. Brale	3000kg 10 mm Ball		500g or Greater Load		
92	-	80.0	87	97	92	87	-	1865	-	-	-
92	-	79.0	86	-	92	87	-	1787	-	-	-
91	-	78.0	85	96	91	86	-	1710	-	-	-
91	-	77.0	84	-	91	85	-	1633	-	-	-
90	-	76.0	83	96	90	84	-	1556	-	-	-
90	-	75.0	83	-	89	83	-	1478	-	-	-
89	-	74.0	82	95	89	82	-	1400	-	-	-
89	-	73.0	81	-	88	81	-	1323	-	-	-
88	-	72.0	80	95	87	80	-	1245	-	-	-
87	-	71.0	80	-	87	79	-	1160	-	-	-
87	-	70.0	79	94	86	78	-	1076	-	99	-
86	-	69.0	78	-	85	77	-	1004	-	98	-
85.6	-	68.0	76.9	93.2	84.4	75.4	-	940	920	97	-
85.3	-	67.5	76.5	93.0	84.0	74.8	-	920	908	96	-
85.0	-	67.0	76.1	92.9	83.6	74.2	-	900	895	95	-
84.7	-	66.4	75.7	92.7	83.1	73.6	-	880	882	93	-
84.4	-	65.9	75.3	92.5	82.7	73.1	-	860	867	92	-
84.1	-	65.3	74.8	92.3	82.2	72.2	-	840	852	91	-
83.8	-	64.7	74.3	92.1	81.7	71.8	745*	820	837	90	-
83.4	-	64.0	73.8	91.8	81.1	71.0	-	800	822	88	-
83.0	-	63.3	73.3	91.5	80.4	70.2	-	780	806	87	-
82.6	-	62.5	72.6	91.2	79.7	69.4	710*	760	788	86	-
82.2	-	61.8	72.1	91.0	79.1	68.6	-	740	772	84	-
81.8	-	61.0	71.5	90.7	78.4	67.7	-	720	754	83	-
81.3	-	60.1	70.8	90.3	77.6	66.7	653*	700	735	81	-
81.1	-	59.7	70.5	90.1	77.2	66.2	-	690	725	-	-
80.8	-	59.2	70.1	89.8	76.8	65.7	-	680	716	80	329,000
80.6	-	58.8	69.8	89.7	76.4	65.3	-	670	706	-	324,000
80.3	-	58.3	69.4	89.5	75.9	64.7	620*	660	697	79	-
80.0	-	57.8	69.0	89.2	75.5	64.1	611*	650	687	78	-
79.8	-	57.3	68.7	89.0	75.1	63.5	601*	640	677	77	309,000

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APENDIX A

Hardness Conversion Chart

Approximate equivalent hardness numbers for carbon and alloy steels

Rockwell				Rockwell Superficial			Brinell	Vickers	Knoop	Scleroscope	Approx. Tensile Strength of Steel (PSI)
A Scale 60kg Diam. Brale	B Scale 100kg 1/16" Ball	C Scale 150kg Diam. Brale	D Scale 100kg Diam. Brale	15N Scale 15kg Diam. Brale	30N Scale 30kg Diam. Brale	45N Scale 45kg Diam. Brale	3000kg 10 mm Ball		500g or Greater Load		
92	-	80.0	87	97	92	87	-	1865	-	-	-
92	-	79.0	86	-	92	87	-	1787	-	-	-
91	-	78.0	85	96	91	86	-	1710	-	-	-
91	-	77.0	84	-	91	85	-	1633	-	-	-
90	-	76.0	83	96	90	84	-	1556	-	-	-
90	-	75.0	83	-	89	83	-	1478	-	-	-
89	-	74.0	82	95	89	82	-	1400	-	-	-
89	-	73.0	81	-	88	81	-	1323	-	-	-
88	-	72.0	80	95	87	80	-	1245	-	-	-
87	-	71.0	80	-	87	79	-	1160	-	-	-
87	-	70.0	79	94	86	78	-	1076	-	99	-
86	-	69.0	78	-	85	77	-	1004	-	98	-
85.6	-	68.0	76.9	93.2	84.4	75.4	-	940	920	97	-
85.3	-	67.5	76.5	93.0	84.0	74.8	-	920	908	96	-
85.0	-	67.0	76.1	92.9	83.6	74.2	-	900	895	95	-
84.7	-	66.4	75.7	92.7	83.1	73.6	-	880	882	93	-
84.4	-	65.9	75.3	92.5	82.7	73.1	-	860	867	92	-
84.1	-	65.3	74.8	92.3	82.2	72.2	-	840	852	91	-
83.8	-	64.7	74.3	92.1	81.7	71.8	745*	820	837	90	-
83.4	-	64.0	73.8	91.8	81.1	71.0	-	800	822	88	-
83.0	-	63.3	73.3	91.5	80.4	70.2	-	780	806	87	-
82.6	-	62.5	72.6	91.2	79.7	69.4	710*	760	788	86	-
82.2	-	61.8	72.1	91.0	79.1	68.6	-	740	772	84	-
81.8	-	61.0	71.5	90.7	78.4	67.7	-	720	754	83	-
81.3	-	60.1	70.8	90.3	77.6	66.7	653*	700	735	81	-
81.1	-	59.7	70.5	90.1	77.2	66.2	-	690	725	-	-
80.8	-	59.2	70.1	89.8	76.8	65.7	-	680	716	80	329,000
80.6	-	58.8	69.8	89.7	76.4	65.3	-	670	706	-	324,000
80.3	-	58.3	69.4	89.5	75.9	64.7	620*	660	697	79	-
80.0	-	57.8	69.0	89.2	75.5	64.1	611*	650	687	78	-
79.8	-	57.3	68.7	89.0	75.1	63.5	601*	640	677	77	309,000