Ballistic Characterization Of A Typical Military Steel Helmet

Mohamed Ali Maher, Dr. Osama Mounir Dawood, Dr. Nabil El Houseiny Awad, Mahmoud Mohamed Younes

Abstract: In this study, the ballistic limit of a steel helmet against a FMJ 9×19 mm caliber bullet is estimated. The helmet model is the typical polish helmet wz.31.The helmet material showed high strength low alloy steel material of 0.28% carbon content and 9.125 kg/m2 areal density. The tensile test according to ASTM E8 showed a tensile strength of 1236.4 MPa .The average hardness value was about HV550. First shooting experiment has been executed using a 9 mm pistol based on 350 m/s muzzle velocity at 5m against the simply supported helmet; complete penetrations rose in this test were in the form of cracks on the helmet surface, and partial penetrations were in the form of craters on the surface whose largest diameter and depth were 43 mm and 20.2 mm consequently .The second experiment was on a rifled gun arrangement, 13 bullets of 9×19 mm caliber were shot on the examined simply supported steel helmet at a zero obliquity angle at different velocities to determine the ballistic limit velocity V50 according to (MIL-STD-662F). Three major outcomes were revealed; (1) the value V50 which found to be about 390 m/s, is higher than the one found in literature (360 m/s: German steel helmet model 1A1). (2) The smallest the standard deviation of the mixed results zone data, the most accurate the ballistic limit is. (3)Similar to the performance of blunt-ended projectiles impacting overmatching targets (t/D) near 1:1 or larger; It was found that the dominating failure mode of the steel helmet stuck by a hemispherical-nose projectile was plugging mode despite of having t/D ratio of about 1:9 (undermatching).

Keywords: Areal density, Ballistic limit, FMJ 9×19 mm, Military standard, Shooting, Steel helmet

———————————— ◆ ————————————

1 INTRODUCTION

Penetration mechanics is a field of applied mechanics that studies the interaction of a projectile with a target. This field covers a wide range of situations and is of interest to engineers of different disciplines. So far, most progress has been made during experimental investigations of the normal perforation of metal plates. [1-3]. The resistance of metallic materials to ballistic penetration depends on parameters which can be classified as projectile-related, impact-related and the target plate-related. Ballistic properties are a complex function of many properties like yield strength, tensile strength, hardness, ductility, charpy impact energy. An optimum combination of strength, hardness and toughness is essential for good ballistic performance .It is indicated that as the hardness of the steel plate is increased so does the ballistic performance up to a certain hardness level beyond which the ballistic performance decreases with increasing hardness. If the hardness is increased further to approach the projectile's hardness, its ballistic performance improves again. In general, the ballistic limit rises monotonically with increasing the target thickness and strength. [4-8]. High strength and great ductility are two vital properties for steel to absorb energy during impact. Similarly, bulletproof steels have been developing towards two directions: one is characterized by high strength, hardness and perforation resistance via heat treatment and grain refinement; the other is to improve the ductility and toughness of steel.

- *Mohamed Ali Maher is currently pursuing master's degree program in mechanical engineering in Helwan University, Egypt. The correspondence Email engineer.madi@yahoo.com*
- *Dr. Osama Mounir Dawood, Chief of Mechanical Engineering. Dept. Helwan University, Egypt*
- *Dr. Nabil El Houseiny Awad Mechanical Engineering. Dept. Helwan University, Egypt*
- *Mahmoud Mohamed Younes Basic Science Dept. Modern University for Technology and Information, Egypt*

Experimental investigations can be divided into three major categories; the first category covers low velocity impact (Vi < 50 m/s). The second covers the other extreme that is high velocity penetration (Vi> 1300 m/s) .The last category covers penetration and perforation in the sub-ordnance and ordnance velocity regime (Vi < 50 < 1300 m/s) [9-12]. To measure armor performance, two types of tests are commonly used, ballistic limit (V50) and resistance to penetration (V0). The V50 test consists of altering the velocity of the threat until a velocity is determined at which the threat is expected to perforate or defeat the armor 50% of the time. The resistance to penetration test consists of shooting a threat at a predetermined velocity numerous times to ensure that the threat does not perforate or defeat the armor (V0)[13-16]. Military Standard (MIL-STD-662F) uses the Bruceton method, which is an "up-and down" approach in which one alters the velocity of the threat to produce either a complete perforation or a partial penetration in the armor. The goal is to end up with an equal number of completes and partials that are within a set velocity range of one another. The Langlie and Neyer methods of determining a V50 also both use preceding results to determine the velocity of the next shot. The main goal in developing them was to overcome the dependence of the Bruceton test on the choice of the predefined step size [13, 16]. Some researchers have indicated that the Langlie method has an advantage in getting a range of mixed results, while the Neyer method has better estimation precision. The important parameter which is often ignored in V50 testing is the variability in the results. Thus, a varied number of complete perforations in a given number of shots is likely to be obtained when repeatedly testing at the same velocity. Also, when determining the V50 value with a specified confidence level, that value will vary by a substantive amount depending on the number of shots. Without a proper understanding of the variability [16], the following might be incorrectly presumed:

1- Consistency in the armor response at same velocities and number of shots.
2- V50 determinations for the same armor should repeatedly yield the same response.
3- Differences in V50 values always indicate a sensitivity difference.

Some striking velocities that are above the limit velocity will not completely penetrate the armor and others below the limit velocity will completely penetrate the armor. Therefore, to ensure against reaching an incorrect conclusion, it is essential to properly appreciate the need to statistically based comparisons. Every test researched contained this error to some extent. For the purposes of this research, this zone is assumed to be small enough not to greatly affect the results. [13, 15]. Military helmets major concern is protection from fragmenting munitions. The Ballistic Resistance Testing portion of existing procedures measure the resistance of the helmet to bullet penetration, but do not measure the intrusion of the back face of the helmet into the protected area (blunt trauma) [17]. This paper reveals through an experimental study the ballistic limit V50 of a steel helmet. This study also depicts the plastic deformations and failure mode of the helmet subjected to localized impact by using a 9×19 mm caliber pistol at 5 meters, and mainly a rifled gun arrangement using a 9×19 mm caliber at 5 meters. The ballistic limit here V50 is defined as the velocity at which the probability of penetration for a specific projectile is 50% .This means consequently that the material and geometry of the helmet and the bullet are specified.

2 EXPERIMENTAL WORK

2.1 MATERIALS

2.1.1 CHEMICAL COMPOSITION

The chemical composition values have been taken over 5 readings from one random sample and analyzed using 2 different (spectrum) instruments by two different laboratory workers.

TABLE 1 *Chemical composition analysis of the steel helmet material*

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Co	Ti
0.28	1.14	1.12	0.013	0.011	0.36	0.96	0.04	0.06	0.11	0.03	0.003
Pb	La	Mg	B	Sn	Zn	As	Bi	Ca	V	Nb	Fe
0.010	0.003	0.003	0.005	0.002	0.013	0.002	0.02	0.002	0.001	0.004	Balance

2.1.2 AREAL DENSITY

The average weight of the helmet was found to be 1.095 kg and the surface area was about 0.12 square meters. Thus, the areal density of this helmet is 9.125 kg/m2.

2.2 MECHANICAL PROPERTIES

2.2.1 HARDNESS MEASUREMENTS

TABLE 2
Hardness measuring instruments used and their ranges

Hardness	Instrument	Scale
Rockwell hardness	Rockwell hardness Tester	150 kg (diam. Brale)
Rockwell Superficial	DRMC250-AFFRI	15 N scale,15 Kg (diam. Brale)
Micro-hardness	Digital Hardness Tester	2N scale , 2 Kg

TABLE 3
Average hardness values of the steel helmet material

	Rockwell (Rc)	Rockwell Superficial (RN)	Micro-hardness (HV)	Final results (Rc)	(HV)
Average Hardness value	52.3	85.8	571.1	52.2	550

* *The hardness values have been registered either from hardness conversion tables or by the hardness instrument itself.*

2.2.2 TENSILE STRENGTH MEASUREMENT

2.2.2.1 EQUIPMENT

Monsanto Tensometer testing machine and Universal testing machine both of 20 KN Capacitywere used to test the samples. Curved samples were flattened on a press and cut on a CP4000 industrial CO2 laser cutting machine according to ASTM E8.

Fig.1. *Curved samples after*

Fig. 2 *Flattenning under hydraulic press*

Fig. 3. *Final shape of the tensile sample extraction from the helmet*

Table 4: *Standard dimensions of 2 samples of the helmet material prepared for tensile test according to ASTM E8.*

As received samples	S 1	S 2
Thickness(T) mm	1.1	1.1
Width(W) mm	6.25	12.5
Gauge length(L_o) mm	25	50
Cross section Area (A) mm²	6.875	13.75
Total length (L) mm	100	200

2.2.2.2 Test & Results:

Flat tensile specimens were prepared according to ASTM E8 standards [18]. It was tested in a Monsanto tensometer testing machine of 20 KN Capacity with a graphing tool and in a universal testing machine of the same Capacity at 3mm/ min testing speed at room temperature.

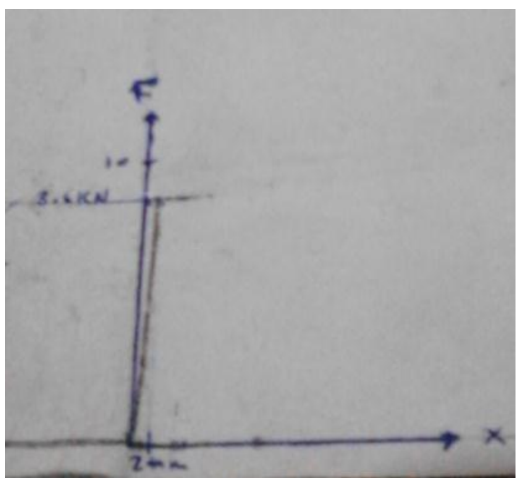


Fig.4. *Force-Displacement curve of the standard tensile sample extracted from the helmet body, it shows a maximum force of 8.6 KN for sample S1. This curve was drawn on the graph drawer of the Monsanto Tensometer machine.*

Table 5 *Tensile test results of the 2 tensile samples*

As received samples	S 1	S 2	Avg.
Maximum force (KN)	8.6	16.8	
Ultimate tensile strength (Mpa)	1250.9	1221.8	1236.4
Total elongation ∆L (mm)	1.9	4.3	
Elongation % ϵ_{max}	7.6%	8.6%	8.1%

2.3 SHOOTING EXPERIMENTS

2.3.1THE FIRST TEST

This test was excuted using a 9 mm pistol with a 9×19 mm bullets, S&B, Luger, at 5 meters distance based on the muzzle velocity of the pistol which is 350 m/s against a simply supported steel helmet.

2.3.2 THE SECOND TEST

The simply-supported steel helmet was impacted with 9 mm FMJ parabellum bullets, The test arrangement is shown in Fig.5. The the projectile mass is 8 g (124 gr.) [19].The projectiles were fired through a rifled gun from a distance of 5 m at zero obliquity angle with the target. The velocities of projectiles were about 390±15 m/s, which were measured using infra-red light emitting diode photovoltaic cells by measuring the time interval between the interceptions caused by the projectile across two transverse beams placed 1 m apart.

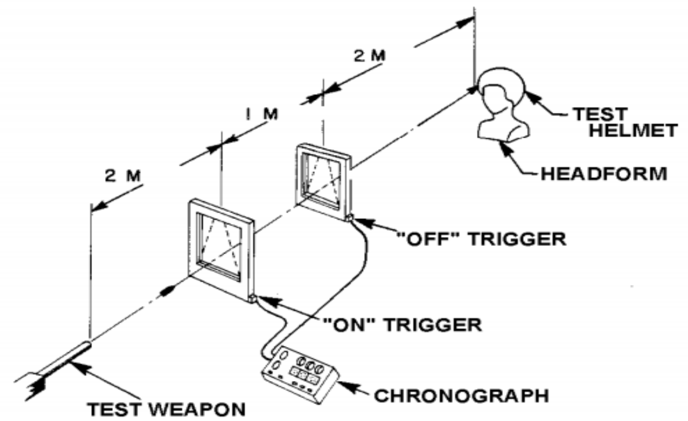


Fig. 5. *Skematic diagram shows the arrangement of the ballistic limit determination test MIL-STD-662F [19-20]*

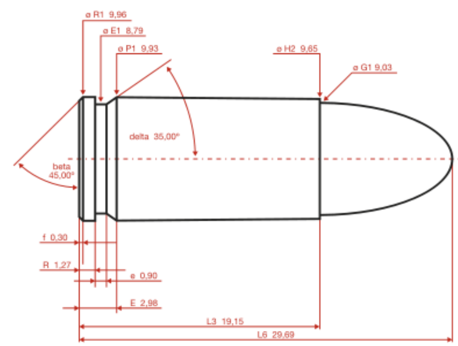
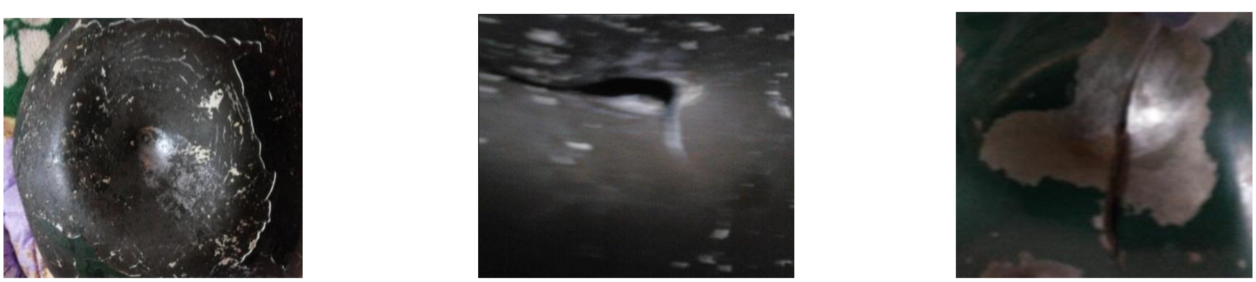


Fig. 6. *Skematic figure shows the 9mmP, Lugar FMJ geometrical dimensions of the*

3 RESULTS

3.1 In the first test; 5 shpots out of 10 penetrated the helmet surface of the helmet forming cracks on the shell, the other 5 shots formed large craters over the helmet surface. The pictures below show the effect of shooting 9×19 mm caliber bullets from 5 meters distance on the helmet from a pistol. It was considered that crater sizes of depths more than 20 mm as partial penetration cases.



(a) (b) (c)

Fig. 7. *The first photo shows the crater formrd on the surface of the helmet of the unpenetrating bullets,the other two photos show the penetration to the helmet surface, a crack through the surface has been created.*

Table 6: *Sizes of Craters formed on the helmets by 9×19 mm caliber bullets from 5 m distance shot from a pistol*

Caliber (mm)	Distance (m)	Crater diam (mm)	Crater depth (mm)
9×19	5	72	16
		83	18
		73	23
		80	21
		70	23
Average		75.6	20.2

3.2 Some longitudinal craters were formed on the helmet surface due to the tangential trajectory of some bullets with respect to the helmet surface.

Table 7 *Sizes of longitudinal Craters formed on the helmet surface by 9×19 mm caliber bullets from 5 m distance*.

Caliber (mm)	Distance (m)	Crater length (mm)	Crater width (mm)	Crater depth (mm)	Test
9×19	5	25	7	3	first test

3.3 In the second test; some partial and some complete penetrations occurred. Taking in account that:

Range of results = highest value – lowest value = 393.15 – 378.24 = 14.91 m/s.
Range of mixed results = highest partial value – lowest complete = 393.15-387.98 = 5.17 m/s.

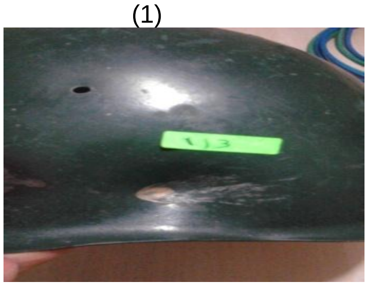
Table 8 *Ballistic performance of the steel helmet against 9×19 mm bullets shot at different velocities from a rifled gun at 5m distance*

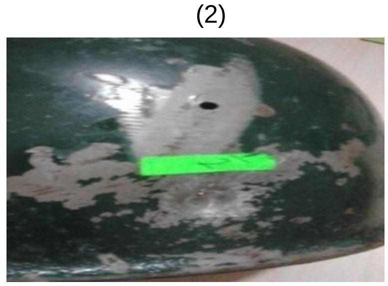
Shot no.	Velocity(m/s)	Penetration	Include Yes/no	Results		
1	378.24	PP	NO	V_{50}	(m/s)	389.995
2	378.52	PP	NO	No. of points		13
3	389.18	CP	YES	High partial	(m/s)	393.15
4	393.15	PP	NO	Low Complete	(m/s)	387.98
5	387.98	CP	YES	Range of results *	(m/s)	14.91
6	383.8	PP	NO	Range of mixed results**	(m/s)	5.17
7	391.6	PP	NO	Required V_{50} margin	(m/s)	27
8	389.37	PP	NO	Humedity:23%		
9	388.69	CP	YES	Temperature:39^{o}c		
10	387.75	PP	NO	Projectile : 9×19 mm, parabellum,Luger .		
11	388.33	PP	NO	Production date:2015 ,Belgium.		
12	389.2	CP	Unfair impact	Date : 5 june 2016		
13	383.06	PP	NO			

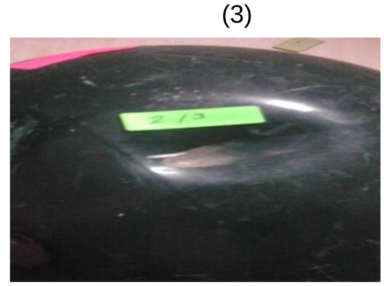

(1)


(2)


(3)


(4)


(5)


(6)

(7) (8) (9)

Fig. 8. *Photos (4, 5, and 6) show highest partial penetration values with craters formed on the shell of the helmet. Photos (3, 7, and 8) demonstrate the complete penetration of the bullets in a plugging shape .The rest of the photos show out of mixed results range impacts.*

(a) (b) (c)

Fig. 9. *Photos (b &c) show the plugging-similar petalling shape occurred in this complete penetration case of photo (a) from the inside direction of the helmet.*

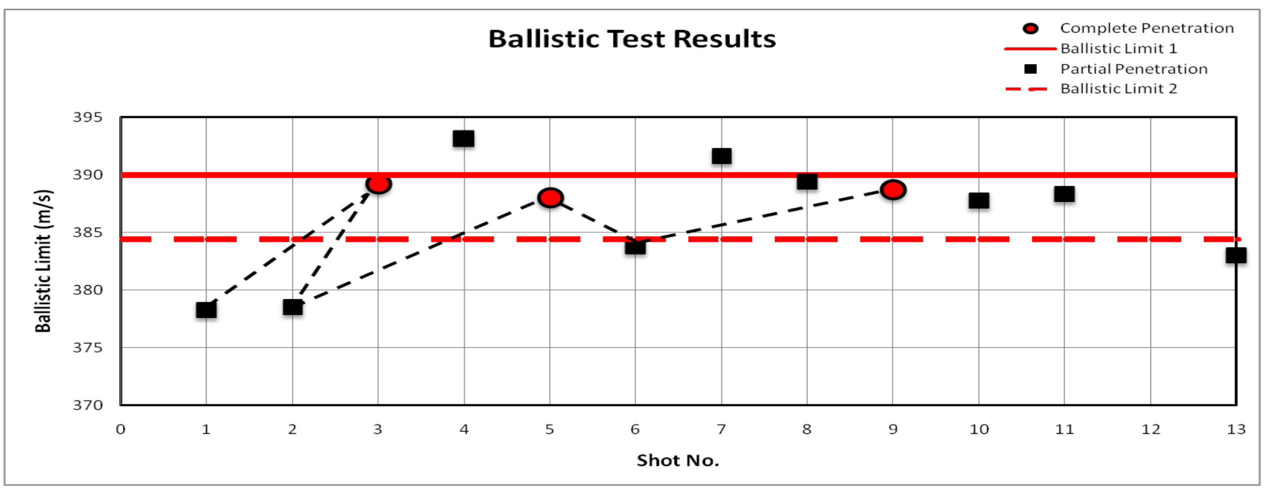


Fig. 10. *The ballistic limit variation based on a different sequence of shooting and different standard deviations.*

Table 9: *Main velocity values measured to estimate the ballistic limit of the helmet*

No.	High Partial penetration (m/s)	Low Complete penetration (m/s)
1	393.15	387.98
2	391.60	388.69
3	389.37	389.18

**Range of mixed results exists only if a partial penetration occurs at a higher velocity than at least one complete penetration.*

3.4 The highest partial penetration value was 393.15 m/s whilst the lowest complete penetration value was 387.98 m/s. Within this range of mixed results, three fair impacts caused complete penetration and other three showed partial penetration. So, the ballistic limit velocity V50 lies within this range. V50 = avg. of the 6 values in table no.9. So, the ballistic limit of this helmet = 389.995 ≈ 390 m/s.

4 DISCUSSION

4.1 First test

a- The cracks occurred in the helmet shell were considered as complete penetration although the projectile itself hasn't actually neither penetrated the shell of the helmet nor passed to the other side, but it caused the shell to fail. [19-21]

b- These cracks formed give also an important indication about the ballistic limit value; since the projectile never passed to the other side, but hardly caused the shell to fail forming cracks; then the projectile velocity at the impact moment (350 m/s) is expected to be nearer to the value of V0 Than the value of V50, Which increase the probability of having higher ballistic limit value than 350 m/s (muzzle velocity of the pistol).

c- The crater depths more than 20 mm were considered to be partial penetration, also, when a bullet strikes a helmet, a cone is formed on the back face of the helmet. The depth of this back face signature (a conical bulge) is required not to exceed a critical value; this is due to the effect of the trauma on the head of the helmet wearer. If the depth exceeds this value, the helmet shell can strike the skull, resulting in behind armor blunt trauma (BABT) (e.g., Carroll and Soderstrom, 1978; Sarron, et al., 2000; Cannon, 2001; Hisley et al., 2011; Prat et al., 2012).[14]

4.2 Second test

a- The range of results was 14.91 m/s, this is not only less than the minimum allowable velocity spread (27 m/s) , but also less than the minimum velocity spread of the two round ballistic test which is (18 m/s) [20] , so it is very accurate result to be obtained for a six-round ballistic test.

b- The ballistic limit calculated here depends on the average value between the highest partial penetrations and the lowest complete penetrations regardless the sequence of shooting i.e. In this test; the ballistic limit velocity was about 390 m/s with a standard deviation of 1.97. However, if a different sequence of shooting had been chosen, and the test was stopped after equal successful partial and complete penetrations(3 in the sex-round ballistic test), a different ballistic limit value might be found.(fig. 10) i.e. using the other shooting sequence, the ballistic limit would be 384.4 with a standard deviation of 5.03.

c- Shot no.12 has been neglected in the ballistic limit calculations due to its incidence coinciding with the partial penetrating shot no.11 [16, 19-20]

d- Most of the failures occurred in the helmet shell were of plugging type except one which was petalling (nearly plugging shape also) although plugging failure mode mostly rises with the blunt ended projectiles for overmatching targets[21-25].

e- The calculated ballistic limit velocity 390 m/s which is higher than the value in literature (360 m/s) seems to be more accurate; because the cracks formed on the helmet surface indicate that the projectile at 350 m/s hardly caused the shell to fail rather than completely passed to the other side forming a plug as it actually occurred with velocities near the calculated ballistic limit 390 m/s.

5 CONCLUSIONS

a- A simply-supported steel helmet of a high strength low alloy steel having 1236.8 MPa tensile strength, HV550 hardness and an areal density of 9.125 kg/m2 was tested against a FMJ 9×19 mm caliber bullet shot at zero obliquity angle from a rifled gun at different velocities .The ballistic limit V50 was determined in this experiment to be about (390 m/s).It seems to be higher than the value found in literature (360 m/s: German steel helmet model 1A1).

b- More than one value for the ballistic limit could be obtained for a single ballistic test. Thus, the smallest standard deviation value in a set of mixed results would give the most accurate value of the ballistic limit in this test. The ballistic limit value will be as accurate as many statistical data are obtained. So, It is obvious that stopping the test directly as the required equal number of complete and partial penetrations gets achieved may lead to an inaccurate estimation of the ballistic limit.

c- Having a ballistic limit velocity higher than the value stated in literature (360 m/s) may refer to a different fixation method or a different calculation methodology. The simply-supported fixture used here may give an overestimation of the ballistic limit value of the armor than when a fixed fixture is used , however, this value is more realistic in battlefield because the helmet is not completely fixed on the soldier's head.

d- Cracks formed on the helmet at striking velocity of 350 m/s (first test) and plugging failure occurred at higher velocities (second test) emphasize that the value of 390 m/s as a ballistic limit velocity outbalances the value of 360 m/s , or rather , the probability of penetration at 350 m/s is less than 50%.

e- Although plugging failure mode mostly rises with the blunt ended projectiles and with t//D ratios near 1:1 or more for overmatching targets , It was found that the hemispherical-nose projectile used here and with t/D ratios near 1: 9 or less for undermatching targets also lead to the same shear plugging mode.

6 FUTURE WORK

a- Studying the effect of using a fixed fixture to the steel helmet against the same bullet.

b- Studying the failure modes and ballistic performance of thin plates within the range: t/D ratios from 0.1 up to 1 with projectiles of hemispherical (round), conical and ogival noses.

c- Studying the effect of strength and ductility of low-carbon alloy steel thin plates on the anti-penetration performance especially in the ordnance velocity regime (500 –1300 m/s

ACKNOWLEDGEMENT

This work was supported technically and financially by the ministry of military production.

REFERENCES

[1] "Experimental and numerical investigation of perforation of thin steel plates by deformable steel penetrators", Predrag M. Elek, Slobodan S. Jaramaz, Dejan M. Micković, Nenad M. Miloradović, Thin-Walled Structures 102 (2016) 58–67.

[2] "Impact loading of plates and shells by free flying projectiles", a review, Corbett G.G, Reid S.R., Johnson W. Int. J. Impact Engng. Vol. 18, No. 2, pp. 141-230, 1996

[3] "Ballistic penetration of steel plates" ,T. Børvik,, M. Langseth", O.S. Hopperstad", K.A. Malo", Int. J. Impact Engng 22 (1999) 855-886

[4] "The Influence of Plate Hardness on The Ballistic Penetration of Thick Steel Plates" , S.N.Dikshit, V.V.Kutumbarao and G.Sundararajan, Int. J. Impact Engng. Vol. 16, No. 2, pp. 293-320. 1995

[5] "Perforation Modes of Metal Plates Stuck by a Blunt Rigid Projectile", Chen Xialwei and Liang Guanjun, Engineering Transactions • Engng. Trans. • 60, 1, 15–29, 2012.

[6] "Effect of heat treatment on mechanical and ballistic properties of a high strength armour steel", P.K. Jena, Bidyapati Mishra, M. RameshBabu, Arvindha Babu, A.K. Singh, K. SivaKumar,T. Balakrishna Bhat, Int. J. Impact Engng 37 (2010) 242–249.

[7] "The influence of projectile hardness on ballistic performance", Charles E. Anderson, Jr., Volker Hohler James D. Walker , Alois J. Stilp, Int. J. Impact Engng 22 (1999) 619-632.

[8] "The ballistic performance of an ultra-high hardness armour steel", an experimental investigation, S. Ryan, H. Li, M. Edgerton, D. Gallardy, S.J. Cimpoeru, Int. J. Impact Engng, 2016.

[9] "Development of a New Armor Steel and its Ballistic Performance", S.Hakan Atapek, Defense Science Journal, Vol. 63, No. 3, May 2013, pp. 271-277.

[10] "Effect of strength and ductility on anti-penetration performance of low-carbon alloy steel against blunt-nosed cylindrical projectiles", Jie Rena, Yuxin Xua,, Jinxu Liub, Xin Lic, Shushan Wanga, Materials Science & Engineering A 682 (2017) 312–322

[11] "Effect of heat treatment on ballistic performance of an armour steel against long rod projectile ", P. Ponguru Senthil, B. Bhav Singh, K. Siva Kumar, A.K. Gogia, Int. J. Impact Engng 80 (2015) 13-23.

[12] "Effect of target thickness in blunt projectile penetration of Weldox 460 E steel plates", Tore Børvik, Odd Sture Hopperstada, Magnus Langsetha, Kjell Arne Maloa, 2003.

[13] "The science of armor materials", I.G.Crouch, Armor Solutions Pty Ltd, Trentham, , Australia, 2017.

[14] "Ballistic Helmets - Their Design, Materials, and Performance against Traumatic Brain Injury", a review, S.G. Kulkarni, X.-L. Gao, S.E. Horner, J.Q. Zheng, N.V. David, Composite Structures, 2013.

[15] "Techniques Used to Estimate Limit Velocity in Ballistics Testing with Small Sample Size" E.Andrew Ferriter, Ian A. McCulloh and William de Rosset, USA, 2005.

[16] Review of Department of Defense Test Protocols for Combat Helmets.; National Research Council. Washington (DC): National Academies Press (US); 2014.

[17] "Bullet resistant helmet "; test procedure; H.P. white laboratory, Inc. HPW-TP-0401.01B, Oct. 1995.

[18] Standard Test Methods for Tension Testing of Metallic Materials ASTM E8

[19] "NIJ Standard for Ballistic Helmets", A Voluntary National Standard Promulgated by the National Institute of Justice December 1981 U.S. Department of justice, National Institute of Justice.

[20] Department of Defense Test Method Standard: V50 Ballistic Test for Armor; MIL-STD-662F, 18 December 1997, DOD, USA.

[21] "Effect of projectile nose shape on ballistic resistance of interstitial-free steel sheets", K.M. Kpenyigba, T. Jankowiak , A. Rusinek ,R. Pesci, B. Wang, Int. J. Impact Engng xxx (2014) 1-12

[22] "Low-velocity impact on high-strength steel sheets: an experimental and numerical study ",G. Gruben, M. Langseth, E. Fagerholt, O.S. Hopperstad , Int. J. Impact Engng, 2015.

[23] "Effect of strength and ductility on anti-penetration performance of low-carbon alloy steel against blunt-nosed cylindrical projectiles", Jie Rena, Yuxin Xua,, Jinxu Liub, Xin Lic, Shushan Wanga, Materials Science & Engineering A 682 (2017) 312–322.

[24] "Numerical simulation of plugging failure in ballistic penetration", T. Børvik, O.S. Hopperstad, T.Berstad, M.Langseth, International Journal of Solids and Structures 38 (2001) 6241- 6264.