Ballistic Behavior of Developed 12.7x99 mm Tungsten Carbide Core AP Projectiles against High Hardness Steel Armor

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Abstract– This paper studies the ballistic behavior of developed 12.7x99mm armor-piercing (AP) projectiles with Tungsten Carbide Core. The ballistic behavior of the new projectiles has been compared with that of traditional 12.7x99mm AP projectiles. The development of AP projectiles aims to improve their penetration abilities against high-strength alloy steel targets. Three different designs have been suggested and modelled in order to compare the penetration capabilities of them. The study includes the ballistics of the three designs, numerical modelling and simulation, using ANSYS 18 (Explicit dynamics), of the three different projectiles as well as the traditional AP projectile in terms of the determination of penetration capabilities of the projectiles when fired at a steel target with a suitable thickness. The stability of the new projectile designs has been also investigated by using PRODAS software. Two of the three designs are chosen for manufacturing according to the previous study. Finally, firing tests have been performed to determine the penetration capabilities as well as the ballistic performance of the designed projectiles. The results show that the stability has been achieved and the penetration ability for one of the developed projectiles is better than traditional AP projectiles by 1.5 times.

I. INTRODUCTION

Nowadays, the need for penetration of armored targets by armor piercing projectiles becomes larger due the high technologies used in armors. As a result of increasing armor thickness/technologies for protecting targets against traditional and current armor piercing projectiles, the aim of this paper is to develop the current 12.7x99mm armor piercing projectile to penetrate large thickness or more advanced armored targets. Small arms projectiles have a penetrating mass or core that may be of hard material such as steel alloy or tungsten alloy, or soft material such as lead. That is depending on whether the projectile is respectively armor piercing (AP-projectiles) and used for perforation of armored targets or used to cause a ballistic trauma and incapacitate a human target (ball-projectiles).

The penetrator core usually sets within a brass jacket for protection of the rifling of the barrel. The ballistic shape of these projectiles is often ogive simply because this is the most effective shape during target penetration and aerodynamic stability. The aspect ratio, i.e. length-to-diameter (L/D) ratio, of these projectiles is typically in the range of (3:1 to 5:1) for projectile's muzzle velocity up to 1000 m/s.

Fig. 1 Shows The Geometry And Composition Of 12.7 Mm Ap Projectile

C. Roberson and P. J. Hazel studied the resistance of silicon carbide targets to be penetrated by a tungsten carbide cored projectile. This study proves that during penetration of the ceramic there is sufficient time so that the cracks in the core are able to grow. Consequently, the core structure is completely compromised and the fragments are dispersed [1]. T. Børvik et al. studied perforation resistance of five different high-strength steel plates subjected to small arms projectiles. This study denotes that when only the hard core is used as projectile, the ballistic limit dropped by 3–5%. [2].

P.J. Hazell et al. studied the effect of gilding jacket material on the penetration mechanics of a 12.7 mm armor-piercing projectile which indicates that removing the tip of the jacket effects a reduction in depth of penetration into a semi-infinite backing layer [3]. Namık and Bulent studied the ballistic resistance of high hardness armor steels against 12.7 mm armor piercing ammunition denoting that when only the steel core is used as projectile, the ballistic limit thickness is decreased by 7%. This indicates that it is reasonable to model only steel core in ballistic limit calculations [4]. Deng et al. studied experimentally the ballistic performance of double layered plates subjected to impact by projectile of high strength.

The results show that the blunt nosed projectiles lose a little amount of mass and their lengths be shorten after perforation. Also, the loss of length and mass becomes larger with increasing their impact velocities compared with ogive nosed projectiles [5]. Namık et al., studied the ballistic behavior of high hardness perforated armor plates against 12.7 mm armor piercing projectile. They noted that the simulations have to include: (a) Asymmetric forces causing the projectile to deviate from incident trajectory, (b) The bullet core fracture and (c) The bullet core nose erosion with these mechanisms. Well agreements were shown between the simulation and experimental penetration depths [6].

T. Børvik et al., studied penetration of granular materials by small-arms bullets. They indicated that the core fracture may give a reduction in penetration capability. The main sources of energy dissipation during impact were found to be Coulomb friction due to particle-particle contact and body-grain sliding, in addition to the change of bullet trajectory during penetration [7].

Yongjuan et al., investigated experimentally and numerically the penetrating of pistol bullet in a soft tissue. They noted that when the bullet is rolling due to instability, the velocity sharply drops. Also, they found the greater of bullet's velocity is, the greater of the resistance acting on the bullet, the earlier the instability of the bullet happens [8]. Liu Susu et al. studied a new motion model of rifle bullet penetration into ballistic gelatin that shows that the head shape has a great influence on the motion of bullet. In order to characterize the behavior of rifle bullets in the gelatin penetration, the changing of the effective wetted area of bullet is studied in the process of penetration and new frameworks are proposed for drag and lift coefficients [9]. Siau et al. reprinted projectile penetration into sand. They studied the effect of relative density of sand, projectile nose shape and it's mass.

That showed that pointed conical head projectile has the lowest ballistic limit. In addition, the mass of projectile has a significant influence on the amount of absorbed energy for all nose shapes [10].

In this study, the traditional armor-piercing projectile is studied. The internal ballistic solution is obtained using analytical model and check of strength of barrel is done. With the help of the old construction, the hard steel core of the armor-piercing projectile is replaced with tungsten alloy core taking in consideration the total mass to be nearly the same as the traditional ones. Many trials are held and the developed projectiles have been constructed taking in considerations the constraints in mass and stability. At first, the traditional AP projectile has been studied to be used as a reference, (for the results of other developed models), regarding its weight, its internal and external ballistic, its numerical simulation results and its experimental penetration results compared with the new three developed models.

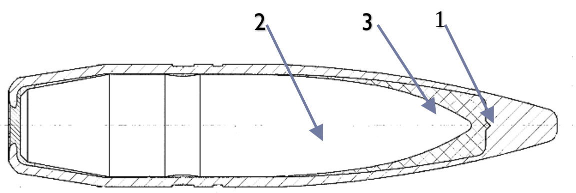
Model one is accepted for its weight, its internal and external ballistics results (accepted stability) but it was excluded for its numerical simulation penetration results. Model two is accepted for its weight, its internal and external ballistic results (accepted stability), its numerical simulation penetration results, but it was also excluded for its experimental results.

Model three is accepted for its weight, its internal and external ballistics results, then it is compared with the current armor piercing projectile numerically and experimentally.

It is important to mention that external ballistic solution using (PRODAS) is carried out to determine the velocity, the drag coefficient and the stability of projectiles along their trajectories [11].

II. STUDIED AND DEVELOPED MODELS

The traditional AP 12.7x99mm model is firstly studied in order to design the new developed 12.7x99mm AP projectiles considering the construction and their corresponding weights. The traditional projectile and its components are shown in fig.2.



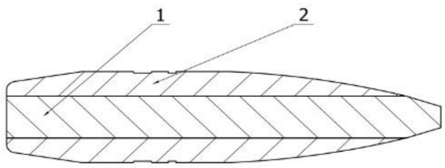
Number	Name	Material
1	Jacket	Brass
2	Core	Lead
3	filler	Aluminum 7075

Fig. 2 The current AP bullet and its components

The total mass of the traditional AP projectile is m_p=45.8 gm. and its core mass is m_{core}=26 gm.

2.1 The Developed AP 12.7x99mm models

2.1.1 Model one



Number	Name	Material
1	Core	Tungsten Core
2	Jacket	Brass

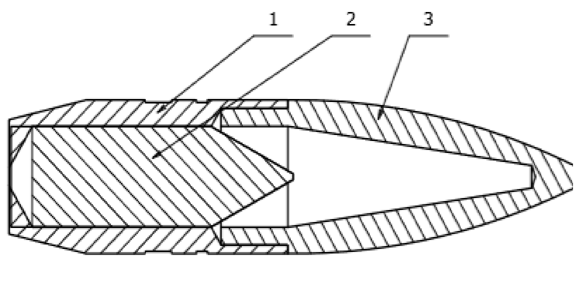
Fig. 3 Model one 12.7x99 mm

The total mass of $B_{3\text{-}127}$ is m_p=59.849 gm and its core mass m_{core}=23.5 gm where its mass is too big compared to original AP bullet where its mass is m_p=45.8 gm so this design will be cancelled.

That leads to think for another technique in the design which is the second model.

2.1.2 Model two

The second model consists of Tungsten Carbide core and Brass Jacket as shown in fig.4



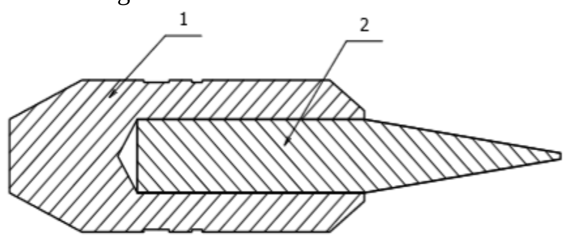
Number	Name	Material
1	Jacket	Brass
2	Core	Tungsten Carbide
3	Ballistic Cap	Brass

Fig. 4 Model two 12.7x99 mm

The total mass is m_p=47gm and its core mass m_{core}=16 gm. For this model, its weight, its internal and external Ballistics results were accepted compared with the traditional AP model. However, it was also excluded for its experimental results due to the penetration ability for the developed projectile is better than the traditional AP projectiles by only 1.1 times.

2.1.3 Model three

Model three 7 consists of Tungsten Carbide core (2) and Brass Jacket (1) With a 2mm base as shown in fig.5



Number	Name	Material
1	Jacket	Brass
2	Core	Tungsten Carbide

Fig. 5 Model Three 12.7x99 Mm

The total mass is mp=45 gm and its core mass mcore=12 gm. For this model, its weight, its internal and external Ballistics results were accepted compared with the traditional AP model. Its numerical simulation penetration results is accepted and finally their experimental firing test shows better penetration than the current AP 12.7x99mm, which will be discussed later.

III. NUMERICAL SIMULATION FOR PENETRATION

Numerical simulation is one of the main approaches used to study the ballistic impact and penetration phenomena, and helps in armors or projectiles design. It also has a low-cost compared to that of experimental studies. The numerical simulation is developed in the environment of ANSYS explicit dynamics. Explicit Dynamics is most suited to events, which take place over short periods of time, a few milliseconds or less. Events that last more than 1 second can be modelled; however, long run times can be expected. Techniques such as mass scaling and dynamic relaxation are available to improve the efficiency of simulations with long durations.

3.1 Energy Error

Energy conservation is a measure of the quality of an explicit dynamic simulation. Bad energy conservation usually implies a less than optimal model definition. This parameter allows you to automatically stop the solution if the energy conservation becomes poor. |For that, the energy error should be minimum, this error is as sown in Eqn. (1).

$$\text{Energy Error} = \frac{|\text{Current Energy} - \text{Reference Energy} - \text{Work Done}|}{\max(|\text{Current Energy}|, |\text{Reference Energy}|, |\text{Kinetic Energy}|)} \quad (1)$$

Where the Reference Energy is equal to [Internal Energy + Kinetic Energy + Hourglass Energy] at the reference cycle. And the Current Energy is equal [Internal Energy + Kinetic Energy + Hourglass Energy] at the current cycle. While the Work Done = Work done by constraints + Work done by loads + Work done by body forces + Energy removed from system by element erosion + Work done by contact penalty forces.

3.2 Strength model

During large deformation the material often starts to yield and deform plastically. When and how this happens is often termed as strength of the material. One of the most used ones for ductile materials is Johnson-Cook's strength model, which takes strain, strain rate and temperature effects into account. This makes it highly appropriate for transient problems where strain rate hardening and thermal softening cannot be disregarded. Johnson-Cook's model contains five constants, A is the yield strength, B is the strain hardening constant, n is the strain hardening exponent, C is the strain rate constant and m is the thermal exponent. ε_p is the effective plastic strain, $\acute{\varepsilon}_p$ is the effective plastic strain rate, $\acute{\varepsilon}_\circ$ is the reference strain rate, and T is temperature. A, B and n can be determined independently of C and m by testing at strain rate 1 s−1 at room temperature, the strain rate term and thermal term thereby equates to one. The remaining terms are typical determined by fitting to data at varying strain rates and temperatures, as shown in Equ.2 [12].

$$Y = \left[A + B\epsilon_p^n\right]\left[1 + C\ln(\dot{\epsilon_p}^*)\right]\left[1 - T^{*m}\right]$$
$$\dot{\epsilon_p}^* = \frac{\dot{\epsilon_p}}{\dot{\epsilon}_0}$$
$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}} \quad (2)$$

We will assume that the Brass jacket is stripped off and has no influence on the whole penetration process so the materials which will be identified are the material of the traditional steel core of the AP 12.7x99mm, the material of the tungsten core of the developed AP 12.7x99mm and the material of the armor (Nonlinear structure steel). These material's mechanical properties are as shown in tables 1, 2.

Table 1 Material data for the Core (Tungsten carbide).

Property	**value**	**units**
Density	14500	Kg/m^3
Specific Heat	134	J/Kg.C
-Johnson Cook Strength		
Strain Rate correction	First order	
Initial yield stress	1.506	GPa
Hardening Constant	0.177	GPa
Hardening Exponent	0.12	
Strain Rate Constant	0.016	
Thermal softening Exponent	1	
Melting Temperature	1449.9	C
Reference Strain Rate (/sec)	1	
Shear Modulus	160	GPa
Gruneisen Coefficient	1.54	
Parameter C1	4029	m/s
Parameter S1	1.237	
Parameter Quadratic S2	0	s/m

Table 2 Material data for Armor (Armox steel).

Property	**value**	**units**
Density	7850	Kg/m^3
Specific Heat	477	J/Kg.C
Young`s Modulus	200	GPa
Poisson's Ratio	0.3	
Bulk Modulus	166.67 e11	GPa
Shear Modulus	76.923 e10	GPa
Yield Strength	200	MPa
Specific Heat	434	J/Kg.C

3.3. Initial conditions and Meshing

In order to start simulation initial conditions must be given and the rigid body must be divided into nodes and elements. The armor is fixed from the four sides and initial velocity is given to the core of the projectile according to the values of External ballistics at a distance 100 m from the muzzle.

Nodes	28878
Elements	25506

The mesh size is (0.3 mm) for both the core and the armor geometry, the steel core of the current AP 12.7x99mm is simulated to impact an armor with 28.1mm thickness with an initial velocity of (863 m/s) while the tungsten core of the developed 12.7x99mm is simulated to impact an armor with 28.1mm thickness with an initial velocity of (895 m/s)

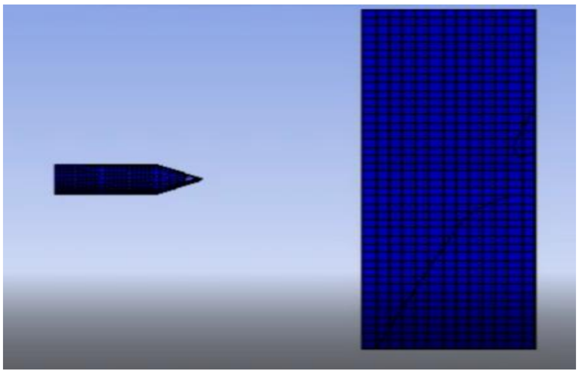


Fig. 6 model two before penetration

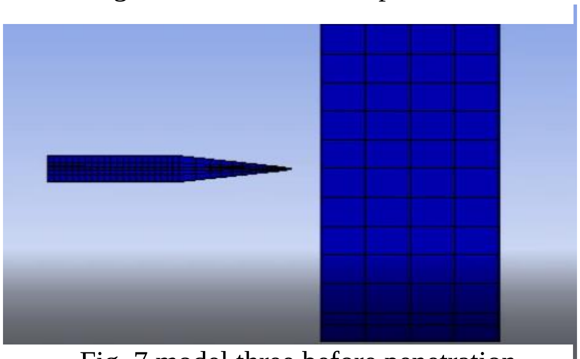


Fig. 7 model three before penetration

3.4. Results

3.4.1 Model two

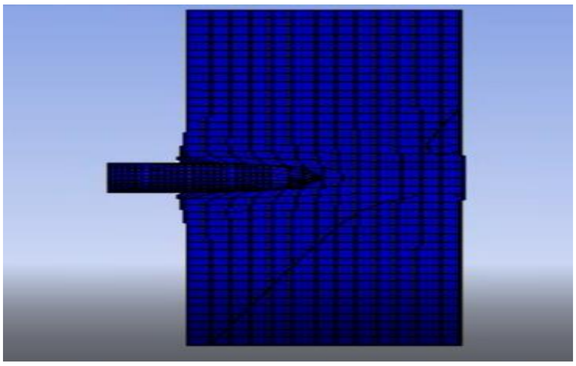


Fig. 8 the model during penetration

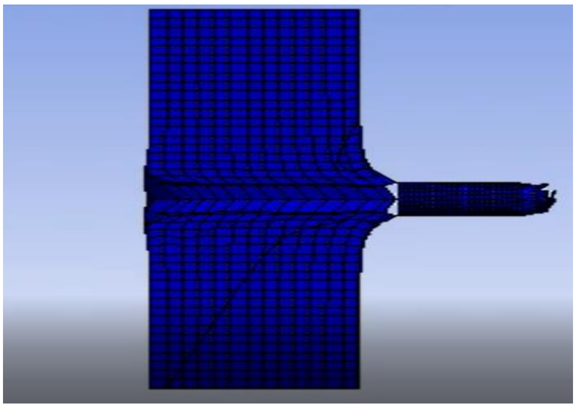


Fig. 9 the model after penetration

3.4.2 Model three

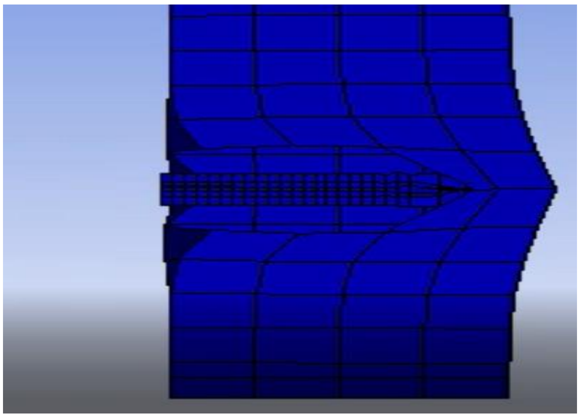


Fig. 10 the model during penetration

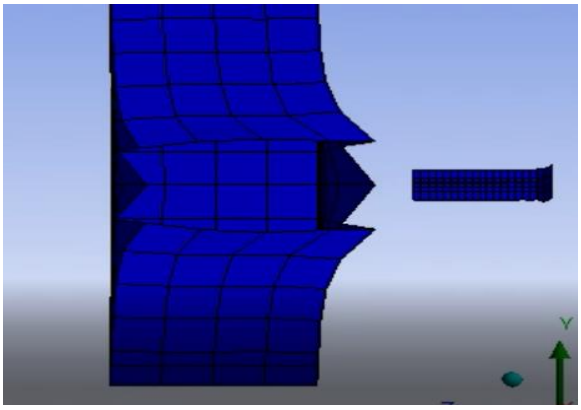


Fig. 11 the model after penetration

The following table and all the simulation results show the following:

Simulation of 12.7x99mm helps us to predict the thickness of target that would be used in the experimental work, which will reduce the no. of trials in the future work. The obtained results will be compared to the experimental results which will be discussed.

Table 3 Different models simulation results

Models	Core	Target	Penetration depth (mm)	Velocity (m/sec.)	Notes
Model two	Tungsten Carbide	Armox	28.1	890	Complete penetration
Model three	Tungsten Carbide	Armox	28.1	901	Complete penetration

IV. PRODUCTION OF THE DEVELOPED BULLET

Production of bullet parts can be performed by using many mechanical production operations i.e. (turning, drilling….). Choice of production method depends on many factors like shape of produced part, material of semi product, dimension of produced part and production facilities.

-The final products

Fig. 9 model two

Fig. 10 model three

Fig. 11 complete bullets

V. FIRING TEST EXPERIMENTS

The impact experiments are performed using a ballistic barrel where the armor piercing projectile and new developed projectiles are fired on fixed targets of relative thickness, and the laboratory work performed for obtaining the necessary data for comparison with numerical findings. Moreover, include the experimental work for the old and new projectiles to make sure of the ability of penetration of new developed bullets compared to that of the armor piercing bullets

-Procedure of Experiment

1) Preparation of the place of firing and correct fixation of the target and barrel

2) Firing the AP projectile and the new projectile and measure their velocities

3) Firing the AP projectile and the new projectile and Check the target after firing to observe penetration depth

4) Check the state of the ballistic barrel and equipment to make sure that there is no damage or cracks due to firing developed projectile.

Fig. 12 ballistic barrel used in firing test

-Targets

The target plates used in the models and experimental work are of ARMOX of thickness 7 mm).

Fig. 13 the target plates with the stand frame

5-Results

1- Firing one bullet of the current AP 12.7x99mm and one bullet of the developed AP 12.7x99mm for measuring their velocities where the Velocities results was 863 m/s and 890m/s and 901m/s respectively.

2- Firing one bullet of the current AP 12.7x99mm against four armor plates with thicknesses (7, 7.3, 7,6.8) with total thickness of 28.1mm and the result was that second plate caught the projectile with a depth of penetration approximately 10mm, and made a bulge in the 3^{rd} plate due to non-accurate fixation.

3- Firing three bullets of the model two developed AP 12.7x99mm against four armor plates with thicknesses (7, 7.3, 7, 6.8) with total thickness of 28.1mm and the results were that:

-two of them penetrated the 1^{st} plate and caught in the 2^{nd} one and made a bulge in 3^{rd} and 4^{th} plates, due to non-accurate fixation.

-the last one completely penetrated the 1^{st} three plates and caught in the 4^{th} one, after editing the fixation, (with red circle in fig.20-21)

4- Firing two bullet of the model three developed AP 12.7x99mm against four armor plates with thicknesses (7,7,7.3,6.8) with total thickness of 28.1mm and the result was:

-one bullet penetrated the 1^{st} two plates and caught in the 3^{rd} one, due to non-accurate fixation.

-the last one had a complete penetration of all of the four plates, after editing the fixation, (with yellow circle)

Results of firing are shown in the following fig.

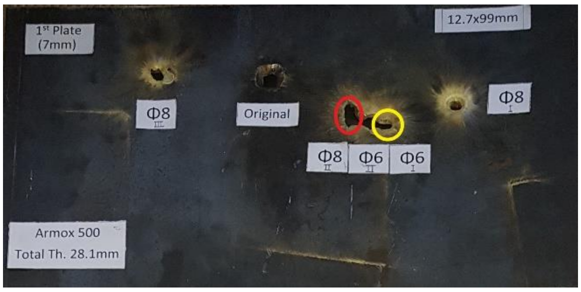


Fig. 14 front of first plate

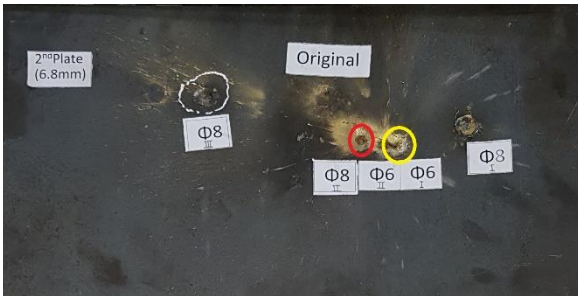


Fig. 15 front of second plate

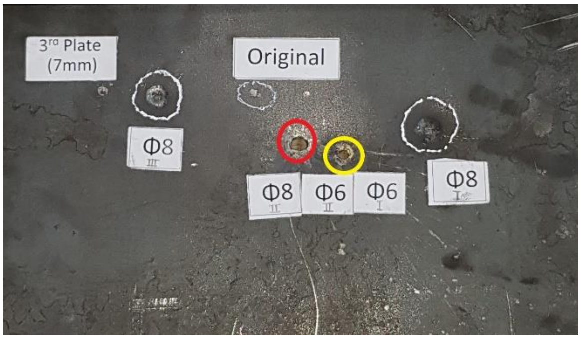


Fig. 16 front of third plate

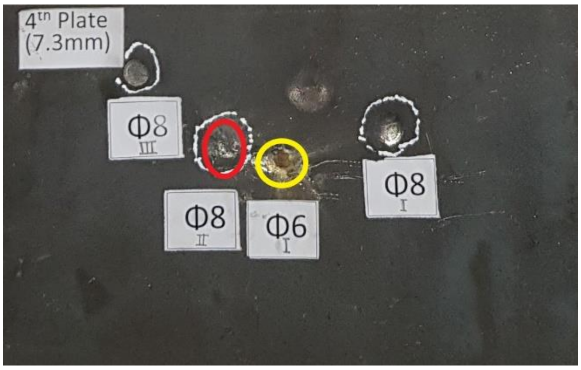


Fig. 17 front of fourth plate

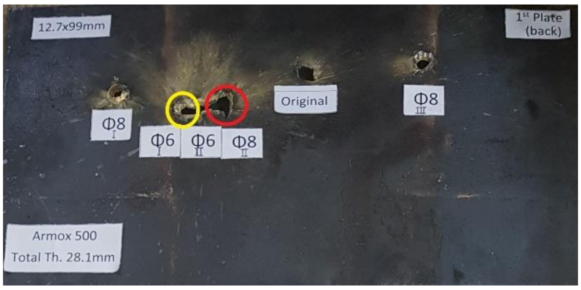


Fig.18 back of first plate

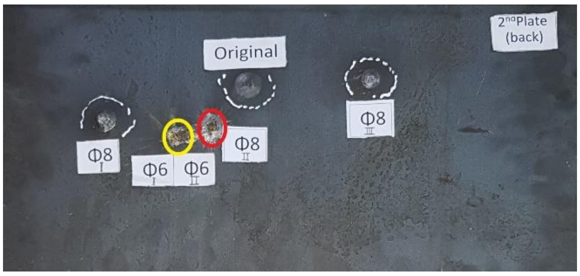


Fig. 19 back of second plate

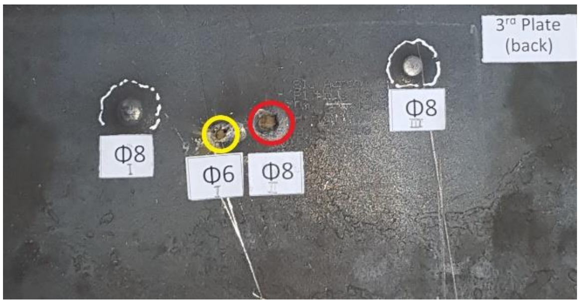


Fig. 20 back of third plate

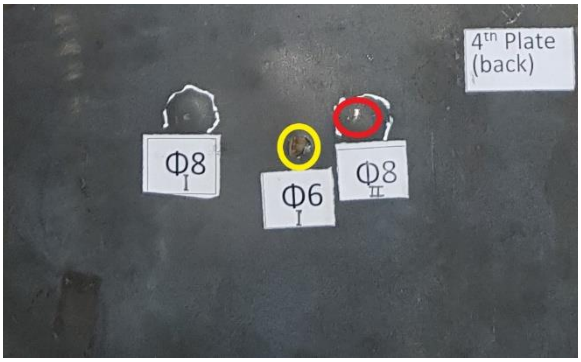


Fig. 21 back of fourth plate

VI. CONCLUSION

The results of this study may show the following conclusions:

1-Final designs of projectile are result of a lot trials till reaching the needed design that is accepted to our manufacturing techniques and mass constraints.

2-Comparison between final designs and current AP showed that the impact energy of core of the original one has higher values than the newly developed ones but due to the better mechanical properties of tungsten carbide core than original hardened steel core, it shows better penetration than the current AP.

3-Numerical simulation shows:

I-Complete penetration of the steel core of the current AP when impact a 20mm armor

II-Complete penetration of the tungsten core of the developed AP when impact a 28.1 mm armor

4-Experiments tests shows:

I- For the developed AP projectiles, when firing against four armor plates with thicknesses (7, 7, 7.3,6.8) with total thickness of 28.1mm,
-Complete penetration of all of the four plates for the 3rd design projectile.
-the 4th plate caught the projectile with a depth of penetration approximately 22mm for the 2nd design projectile.

II- For the current AP projectile when firing against four armor plates with thicknesses (7, 7, 7.3,6.8) with total thickness of 28.1mm and the result was that second plate caught the projectile with a depth of penetration approximately 10mm and a bulge in the 3rd plate.

5- Numerical simulation shows better penetration ability of the developed bullet than the current AP bullet by 1.6 times while Experimental firing tests shows better penetration ability of the developed bullet than the current AP bullet by 1.5 times.

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