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Experimental and numerical research on ballistic performance of carbon steels and cold worked tool steels with and without Titanium Nitride (TiN) coating

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Abstract. It is extremely important to be aware of the ballistic performances of engineering materials in order to be able to choose the lightest armor providing full ballistic protection in civil and military applications. Therefore, ballistic tests are an important part of armor design process. In this study, ballistic performance of plates made of carbon steel and cold worked tool steel against 7.62 mm AP (armor-piercing) bullets was examined experimentally and numerically in accordance with NIJ standards. Samples in different sizes were prepared to demonstrate the effect of target thickness on ballistic performance. Some of these samples were coated with titanium nitride using physical vapor deposition (PVD) method. After examining all successful and unsuccessful samples at macro and micro levels, factors affecting ballistic performance were determined. Explicit non-linear analyses were made using Ls-Dyna software in order to confirm physical ballistic test results. It was observed that the ballistic features of steel plates used in simulations comply with actual physical test results.

Keywords: ballistic performance; Titanium Nitride (TiN); bullet impact; explicit non-linear analysis

1. Introduction

Research and development operations towards defense industry are increasing rapidly in developing countries. Technological advances accelerate development of firearms, and accordingly, development of durable armor materials is becoming important. The most important advantages of weight reduction are improving mobility and reducing energy consumption. Coated steel alloys with weight reduction are being widely used in tank, armored personnel carriers due to their high specific strength. Similarly, titanium alloys are among potential armor materials due to their good mechanical qualities (Atapek 2012, Karagöz *et al*. 2007). Protective material selection in accordance with the type, geometry and penetration kinetics of bullets fired from a firearm, penetrator or fire particle is an important topic. Among all these materials, rolled homogenous armor steels (RHA, Rolled Homogeneous Armor) are being used as protective material especially in military platforms for various personnel and ammunition carriers (Ford 2006).

There are many experimental and numerical ballistic performance studies of steels with different qualities and features, and other engineering materials in the literature. Kpenyigba *et al*. (2015), using different projectile nose shapes, have conducted an experimental and numerical study on the ballistic performance of thin steel plates. Ponguru *et al*. (2015) and Sukumar *et al*. (2015) have investigated the effects of tempering on ballistic performance. According to Ponguru, the ballistic performance increases with decreasing temper temperature but the performance improvements are not proportional to the strength increase caused by the temper processing. Iqbal *et al*. (2015), have established the characterization of mild steel and examined its ballistic performance physically and numerically, where numerical calculations were conducted using ABAQUS/Explicit software. Russell (2014), have examined the ballistic behavior of stainless steel numerically. Ballistic performances, namely the effects of dynamic strength, dynamic hardness and critical failure strain on ballistic performance, of Ti-alloys such as Ti684, Ti−5Al−5Mo−5V−3Cr−1Zr have been examined (Li *et al*. 2014, Wang *et al*. 2015). Wang *et al*. (2015), studied the ballistic performance of protective material made of woven fabric physically and numerically. According to the results obtained, large crimp fabric is prone to form high stress at the edge of the contact of the fabric with the bullet. In practice, ceramic-based composite materials, aluminum foam, metal matrix composite materials are used as armor material (Gillespie 2011, Shokrieh and Javadpour 2008, Naik and Shrirao 2004). Übeyli *et al*. (2010), examined the ballistic performance of dual phase steels. They reported that increasing the amount of martensite in dual phase steel increased ballistic strength. Balakrishnan *et al*. (2013), investigated ballistic performance of armor grade quenched and tempered steel welded joints. Lane *et al*. (2002) and

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Sangoy *et al.* (1988) examined the ballistic performances of steels with different chemical compositions. Gálvez *et al.* (2009), examined fracture behavior both in static and dynamic conditions of high strength armor steel Armox500T. Jena *et al.* (2010), determined ballistic impact behavior of a high strength armor steel and Al-7017. The ballistic result of the Al-7017 alloy is compared with that of the steel by Ramavat *et al.* (2012), who found out that predictive capability against perforation of 7.62 mm bullet is accurate with Radioss non-linear explicit analysis. Findik, and Tarim (2003) and Tarim *et al.* (2002) have investigated ballistic impact efficiency of polymer composites. C-scan method is used. 28 and 36 layers of composite specimen is able to stop the bullet. Kilic *et al.* (2015) applied a hybrid method using FEM and artificial neural network to define ballistic limit value for Armor steels. Rakvag *et al.* (2013) examined deformation and fracture modes of steel projectiles during impact.

According to the literature, it is seen that expensive and high strength steels are used in ballistic applications. In this study, readily available carbon steels (1040) and cold worked tool steels (2842) were used as an alternative materials since armor steels are high-cost materials and there are problems obtaining them. These steels were coated with Titanium Nitride (TiN) using PVD coating method, and their ballistic performances were investigated. Ballistic tests were conducted both physically and numerically.

2. Experimental setup

2.1 Sample preparation

Samples were prepared from two different materials in the study. First group samples were prepared from carbon steel (1040) in 9 mm and 14 mm thick, 50 × 50 mm plates. Second group samples were prepared from cold worked tool steel again in 9 mm and 14 thick, 50 × 50 mm plates. One of the 9 mm and 14 mm thick plates made of both material was coated with approximately 1-1.5 μm TiN using PVD method. Mechanical properties of the materials used were as follows for 1040 steel and 2842 steel in Table 1. Samples to be TiN coated through PVD method were placed in a high-vacuum cabin and coated with TiN using a plasma created with reactive gases (O2, N2) and ionized through high energy.

After PVD coating, the thickness of coating was determined with metallographic examination. Fig. 1 shows examples of samples coated and not coated with titanium nitride.

Coating thicknesses of samples were calculated from the images obtained from SEM. In Figs. 2, 3, 4 and 5, light colored sections show metal surface, whereas dark colored sections indicate bakelite surface, while the yellow section in the middle shows the coating.

Table 1 Mechanical properties of 1040 and 2842 steels

Steels	Young's modulus (E) [MPa]	Density (ρ) [mg/mm^3]	Poisson ratio (v)	Yield stress (σ) [MPa]
1040	210000	7.8e-09	0.3	390
2842	210000	7.8e-09	0.3	480

Fig. 1 Samples coated with TiN through PVD method

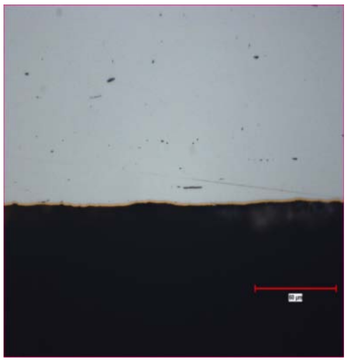

Fig. 2 Coating applied to 9 mm thick 1040 steel

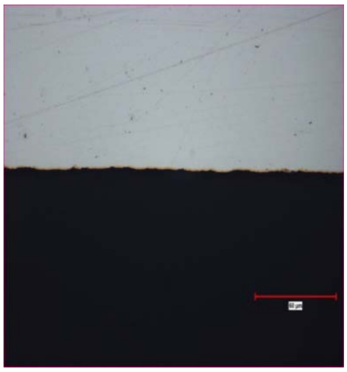

Fig. 3 Coating applied to 14 mm thick 1040 steel

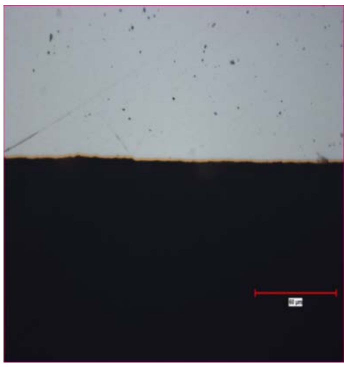

Fig. 4 Coating applied to 9 mm thick 2842 steel

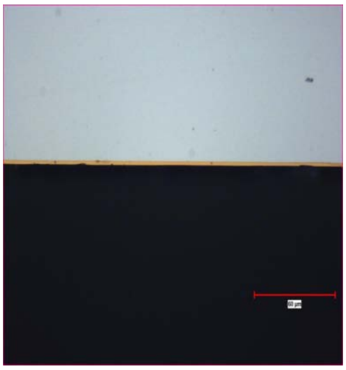

Fig. 5 Coating applied to 14 mm thick 2842 steel

Fig. 6 7.62×51 mm bullet

Table 2 Features of bullets used in ballistic tests

Bullet	7.62×51 mm
Firing distance (m)	15
Core diameter (mm)	7.62
Core weight (g)	10.60
Casing weight (g)	11.85
Casing length (mm)	51
Gunpowder amount (g)	2.79
Muzzle speed (m/s)	869

2.2 7.62×51 mm NATO AP ammunition

In the physical tests of samples whose ballistic impact features to be examined, NIJ standard – an American standard adopted by NATO – was used, while the tests were performed with 7.62×51 AP (armor piercing) bullets according to NATO IV level. Features of bullets used in ballistic test are given in Table 2. Fig. 6 shows 7.62×51 bullet.

2.3 Ballistic tests

All of the prepared samples were subjected to ballistic tests. Shots were fired with long barreled rifles, MIL-STD-662E standard ballistic shooting test was performed with 0 degree in terms of determining ballistic limit velocity (V_{50}). 7.62 mm AP steel core bullet's muzzle exit velocity is approximately 869 m/s. These velocity values were determined with velocity scale device for each shot. There was a 15 m distance between bullet's launch location and the target. In the ballistic tests, bullet velocities were varied between 860 and 869 m/s and the average velocity was recorded as 864 m/s on average. Each sample was subjected to single shot, bullets were fired perpendicularly to targets. Ballistic performance is about bullet's entering the target completely, and piercing through it. In order for a sample to be successful, it must stop the bullet and be non-perforated by the bullet. Samples satisfying these conditions (non-perforated) are considered successful.

2.4 Results

Ballistic examination started with 1040 steel, then samples with no operations and samples with titanium nitride coating were subjected to shots, respectively. Firstly, 9 mm thick 1040 steel was mounted on the apparatus and made ready for the shot. After the shot, each sample was photographed separately. Fig. 7 shows the 9 mm thick 1040

Fig. 7 9 mm thick 1040 steel after the shot

Fig. 8 9 mm thick titanium nitride coated 1040 steel after the shot

Fig. 9 14 mm thick 1040 steel after the shot

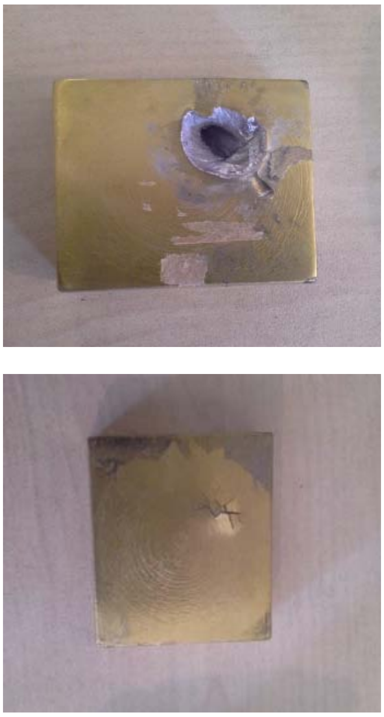

Fig. 10 14 thick titanium nitride coated 1040 steel after the shot

steel after the shot. Figs. 8 shows 9 mm thick titanium nitride coated 1040 steel after the shot. Ballistic examinations continued with 14 mm thick samples. Fig. 9 shows the 14 mm thick 1040 steel after the shot. Fig. 10 shows 14 mm thick titanium nitride coated 1040 steel after the shot.

Upon examining the ballistic test results of 9 mm thick samples with no operation and samples with titanium nitride coating, it was observed that the samples could not stop the bullets. In 14 mm thick samples, sample with no operation was broken, while titanium nitride coated sample stopped the armor piercing bullet.

Fig. 11 shows 9 mm thick 2842 steel after the shot. Fig. 12 shows 9 mm thick titanium nitride coated 2842 steel after the shot. Ballistic examinations continued with 14 mm thick samples. Fig. 13 shows 14 mm thick 2842 steel after the shot. Fig. 14 shows 14 mm thick titanium nitride coated

Fig. 11 9 mm thick 2842 steel after the shot

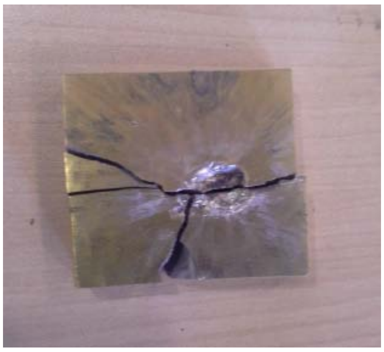

Fig. 12 9 thick titanium nitride coated 2842 steel after the shot

Fig. 13 14 mm thick 2842 steel after the shot

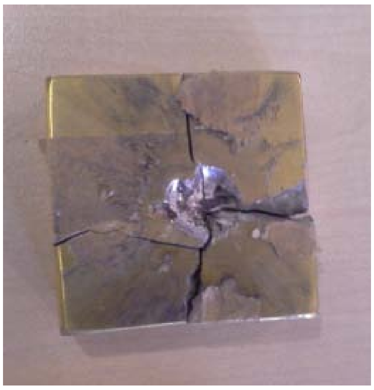

Fig. 14 14 mm thick titanium nitride coated 2842 steel after the shot

2842 steel after the shot.

Upon examining the ballistic test results of 9 mm and 14 mm thick samples with no operation and samples with titanium nitride coating, it was observed that the samples were damaged, however the bullet did not pierce through sample, rather broke it by cracking.

3. Simulation of bullet impact on steel plates

In this section, Ls-Dyna explicit non-linear analyses were carried out to confirm physical ballistic test results. It was found that the ballistic features of steel plates used in simulations comply with actual physical test results.

3.1 CAD Data of steel plate and bullet

9 mm and 14 mm thick steel plates and ¼ model of 7.62×51 mm bullet shown in Fig. 15 are given in Fig. 16. Steel plates and bullet layer model were created in Catia software. Sizes of steel plates are 50×50 mm.

3.2 Finite element modelling

Finite element models belonging to bullet and steel plate whose CAD models given in Fig. 16 were created. This model will present steel plate behavior against the dynamic loading of 7.62×51 mm AP ammunition using Ls-Dyna explicit non-linear analysis. Fig. 17 shows the FEM model created. In this study, two different steel plates in two different thickness values (9 mm and 14 mm) were used. The steels used are 1040 carbon steel and 2842 cold work tool steel. In addition, steel plates made of both materials were coated with 1-1.5 μm thick titanium nitride.

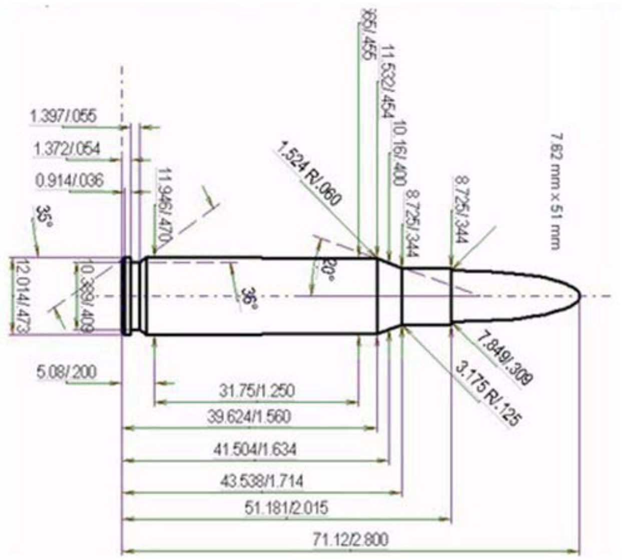

Fig. 15 7.62x51 mm NATO ammunition (URL 2016)

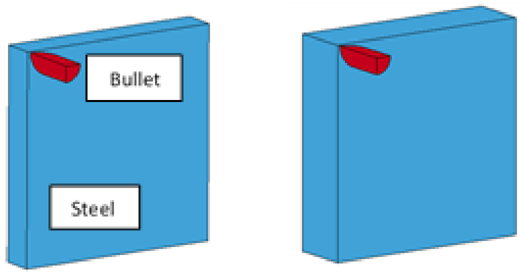

Fig. 16 CAD model of steel plate and bullet

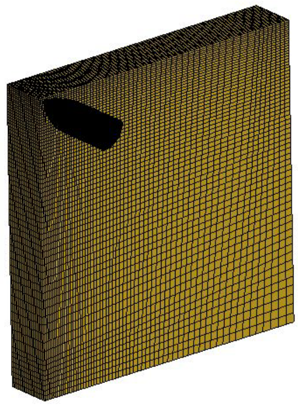

Fig. 17 FEM model of steel plate and bullet

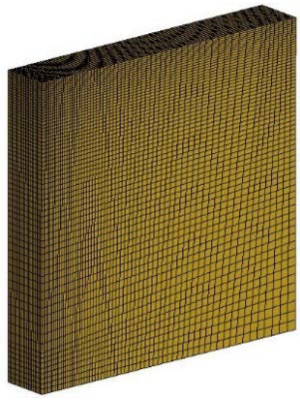

Fig. 18 FEM model of steel plate

Fig. 19 FEM model of bullet

While creating the FEM model, 3D hexahedral elements were used for steel plates. As the material model, elasto-plastic material (MAT/PLAS_JOHNS) is selected. Two different steel plate material feature are identified. Mechanical properties of 1040 and 2842 steels were shown in Table 1. These values are used in virtual analyses. Solid section is chosen as section. Fig. 18 shows the FEM model of steel plates.

The used bullet is 7.62×51 mm NATO AP ammunition. Average bullet velocity is 864 m/s. Rigid material (MAT_RIGID) is selected as material model. 3D hexahedral elements are used for bullet. Bullet material features are;

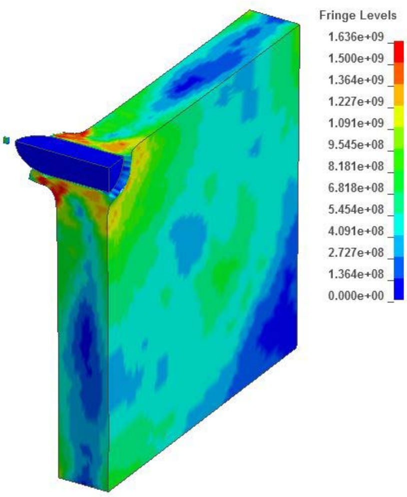

Fig. 20 1040 steel plate after impact

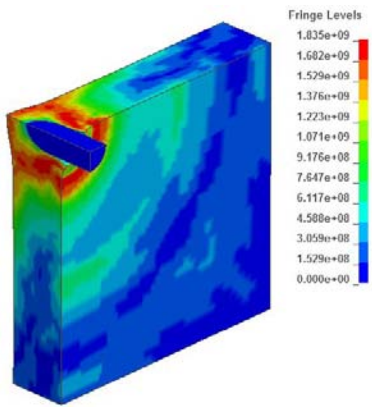

Fig. 21 1040-TiN film steel plate after impact

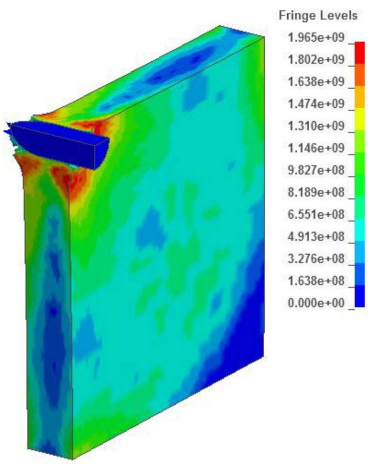

Fig. 22 2842 steel plate after impact

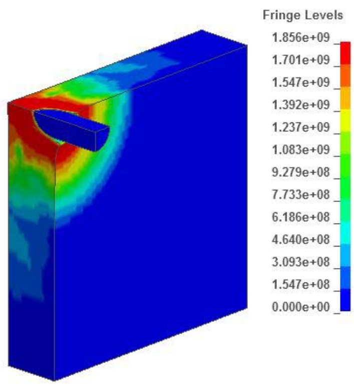

Fig. 23 2842-TiN film steel plate after impact

Table 3 Comparative results for actual test data and simulation test data for 1040 steel

Steel type	Parameters	Simulation	Actual test
1040	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	9 mm	9 mm
	Results	penetration	penetration
1040-TiN film	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	9 mm	9 mm
	Results	penetration	penetration
1040	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	14 mm	14 mm
	Results	penetration	penetration
1040-TiN film	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	14 mm	14 mm
	Results	No through penetration	No through penetration

Young's Modulus (E): 210000 MPa, density (ρ): 7.8e-9 $\mathrm{mg/mm^3}$, Poisson ratio (υ): 0.3. Solid section is chosen as section. Fig. 19 shows the FEM model of bullet.

3.3 Pre-processing

When the bullet impacts the steel plate, it is necessary to divide the plate and bullet into a finite number of regions called elements for modelling high speed impact simulation, penetration and deformation processes. To improve reality of simulation of the impact problem, the finite element mesh needs to be relatively dense in regions that experiences high stress gradients and large deformations. Figs. 17, 18 and 19 show relatively coarse mesh constructed at the region, far from the impact zone. This was done in

Table 4 Comparative results for actual test data and simulation test data for 2842 steel

Steel type	Parameters	Simulation	Actual test
2842	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	9 mm	9 mm
	Results	penetration	No through penetration
2842-TiN film	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	9 mm	9 mm
	Results	penetration	No through penetration
2842	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	14 mm	14 mm
	Results	No through penetration	No through penetration
2842-TiN film	Bullet type	7.62×51 mm	7.62×51 mm
	Bullet mass	10.6 g	10.6 g
	Bullet velocity	864 m/s	864 m/s
	Steel plate size	50×50 mm	50×50 mm
	Steel plate thickness	14 mm	14 mm
	Results	No through penetration	No through penetration

order to minimize the computational time. Also ¼ bullet model is used in order to minimize the computational time. Initial velocity is 864 m/s along –Z-direction. “Contact eroding surface to surface” was chosen as type of contact.

3.4 Results of FEA

As a result of the simulations, it was found that bullet was able to penetrate through the 1040 steel plate (9 mm) with and without TiN film. It can be seen in Fig. 20.

Also, it was found that bullet was able to penetrate through the 1040 steel plate (14 mm) without TiN film. But it was found that bullet was unable to penetrate through the 1040 steel plate (14 mm) with TiN film. However, the bullet cracked the steel plate. It can be seen in Fig. 21.

As a result of the simulations, it was found that bullet was able to penetrate through the 2842 steel plate (9 mm) with and without TiN film. It can be seen in Fig. 22.

Also, it was found that bullet was unable to penetrate through the 2842 steel plate (14 mm) with and without TiN film. However, the bullet cracked the steel plate. It can be seen in Fig. 23.

Physical and numerical comparative test results of 1040 carbon steel and 2842 cold work tool steel are given in Tables 3 and 4. It was found that the ballistic features of steel plates used in simulations comply with actual physical test results.

4. Conclusions

It was found after ballistic examination that 14 mm thick sample made of 1040 steel with no coating cannot hold the bullet, while 14 mm thick sample made of 1040 steel with TiN coating is able to stop the bullet. This might lead us to the conclusion that titanium nitride coated sample absorbs more energy compared to the uncoated sample and behaves in a more durable manner. Therefore, it is possible that ballistic performances of steel plates may be improved through increasing TiN coating thickness and/or trying different coating methods. Samples made of 2842 steel were found to have a more brittle and fragile structure. During the shots, no bullet was able to pierce through the samples, however the samples cracked and broke while absorbing energy. For samples subjected to ballistic test shots, it was found that the material demonstrates a better ballistic performance as the coating layer thickness increases. Moreover, as the hardness increased, it was observed that the bullet core eroded more, and therefore ballistic performance increased. However, it was determined that increased hardness cannot be the sole criterion for ballistic performance.

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