Original scientific papers UDK 616.71−001.5:669.14.018.8
doi: 10.7251/COMEN1602137B

A NEW GENERATION OF ARMORED STEEL PLATES

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Abstract: The engineers of PROTAC d.o.o. and the biggest Slovenian steelwork ACRONI d.o.o., in cooperation with domestic and foreign institutions of science, have been designed and developed a new generation of armored steel PROTAC 500. Steel PROTAC 500 belongs to the group of high strength low alloy (HSLA) steels. It is made in steelwork ACRONI d.o.o. by the standard industrial procedures. The relevant mechanical properties of that steel are achieved by corresponding heat treatment procedure: quenching and tempering.

Preliminary tests of the mechanical properties of the steel have indicated the possibility of using steel PROTAC 500 for light armored vehicles. The presented work studied the response of new generation armored steel plates PROTAC 500 to the ballistic testing with armored piercing bullets with a core of tungsten carbide, charge 7.62 mm. However, the interactions between the piercing bullets and the armored steel plate were also investigated. The most obvious and significant phenomena in penetrating of the piercing bullets Nammo AP8 in steel target PROTAC 500 are strain hardening of steels, the appearance of cracks and local failure, adiabatic shear bands (ASB) with related phase transformations, and melting as well as alloying at the interface between bullet and steel plate.

Keywords: steel, plate, armor protection, adiabatic shear band (ASB).

1. INTRODUCTION

The selection of the appropriate armored material is crucial to ensure the adequate safety and mobility transport systems [1]. When selecting or developing the appropriate materials for the armor, it is necessary to achieve the best possible compromise between the required mechanical properties of materials, minimizing the density and the final price of the product [2]. With the appropriate production technology, which includes synthesis, hot forming, heat treatment, etc. [3,4], high strength low alloy steel of good functional properties at affordable prices can be produced. By improving the strength and toughness of the steel,the required thickness and the weight of the steel shell is reduced. Such steels are competitive to other materials for the armor [5].

In the context of this study, we carried out a ballistic test of high strength low alloy steel PROTAC 500, whose mechanical properties are collected in Table 1.

Table 1. Mechanical properties of steel PROTAC 500

Hardness	480 – 530 HB
Yeald strength $R_{P02,}$	1200 MPa
Tensile strength R_m	1600 MPa
Elongation A_5	8 %
Impact toughness (at testing temperature − 40 °C)	20 J

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Steel PROTAC 500 belongs to the group of high strength low alloy (HSLA) steels. It is made in Slovenian steelwork ACRONI d.o.o. by the standard industrial procedures, and the relevant mechanical properties are achieved by quenching and tempering.

Preliminary tests of the mechanical properties of the steel have indicated the possibility of using steel PROTAC 500 for light armored vehicles. Ballistic testing was performed by using 7.62 mm armored piercing bullets of the Swedish manufacturer Nammo (German standard VPAM, level 11, and the American standard STANAG 4569, Level 3), to examine the interaction between a bullet and a steel plate. Armored piercing bullets, containing the rigid core (generally of high strength steel), which results in the conversion of the total kinetic energy of the bullets to the deformation of the target. The peculiarity of this bullet is the core of tungsten carbide (WC-Co) [6]. When the bullet hits its target, first the formation of pressure waves (cyclic stress) are formed, that spread through the target material and shall be deducted from the back side of the target as tensile waves (Figure 1).

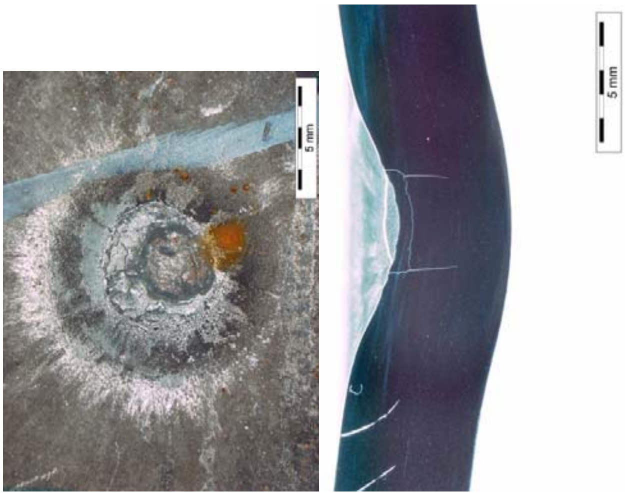


Figure 1. Point of projectile shot (left) with cross-section of the plastic deformed plate (right)

These waves reinforce the material, at a certain intensity of interaction between the waves of pressure or tension and can lead to the formation of adiabatic shear bands (ASB), cracks and crack growth. The material resistance to compressive and tensile waves is improved by increasing the strength and toughness. The deformation mechanisms at low strain rate are relatively homogeneous, while at extremely high speeds, they are more complex. Here it comes to the extreme strain localization in narrow bands called adiabatic shear bands (ASB). The belt is very hot during the deformation, whereby there a transformation of the austenite phase originates, after the load it is rapidly cooled, which results in the transformation to martensite, and thus a high hardness and brittleness of the steel in the ASB occurs. The shear zones are therefore weak areas in the steel.

2. EXPERIMENTAL WORK

For the ballistics testing, a steel PROTAC 500 testing plate with dimensions of 500 x 500 x 20.8 mm was used. Six shots were conducted under the terms of the standard VPAM and STANAG 4569 (Table 2) [6].

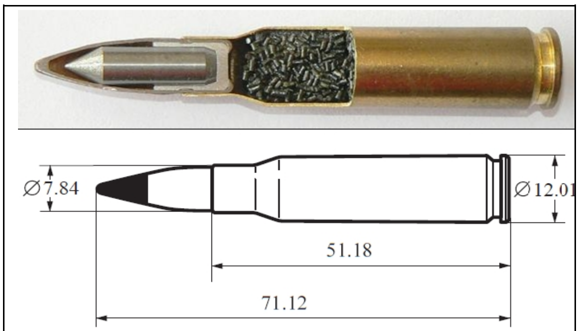
Nammo AP8 is the cartridge of an armored penetrating bullet caliber 7.62 x 51 mm (.308 Winchester)[6]. American label of the cartridge is the M993. It tends to be used against targets with light armor.

Table 2. Terms of ballistic test according to the standard VPAM and STANAG 4569 [6]

Producer	Nammo AP8
Standard	VPAM – level 11
Caliber	.308 Win
Cartridge	FMJ/PB/WC
Bullet mass	8.4 ± 0.,1 g
Bullet speed	930 ± 10 m/s
Distance from target	10 ± 0.5 m
Bullet energy	3633 J

Bullet is capable of destroying such targets by 2 to 3 times the distance from the armored piercing of bullets with steel cores. The bullet is made up of a core of tungsten carbide, mounted in an aluminium cup shell made of steel coated with brass. In Figure 2 are the properties of the bullet Nammo AP8, and image of transected cartridge and the cartridge sketch with the main dimensions [6].

After the ballistics test was excluded from the testing panel, three testing samples were cut. The first sample was then cut in several planes perpendicular to the direction of the shot, the other two samples were cut through the penetration of bullets in a plane parallel to the direction of the shot. For the surface, metallographic analysis samples were etched with an aqueous solution of ferric chloride. Prepared in this way, the surface was examined by metallographic investigation methods. Analysis of macro and microstructure were performed on an optical microscope Olympus BX61. We were interested in particular areas with a different microstructure of the base and the places where the cracks and adiabatic shear bands (ASP) are found [7]. This was followed by analysis with the scanning electron microscope (SEM) JEOL 5610 (Figure 3), which allows the observation of microstructure and qualitative and quantitative chemical analysis [8].



Bullet mass: 8.3 g
Core mass: 5.9 g
Core diameter 5.5 mm
Core point: angle 58 °
Bullet cover material: Steel and brass
Bullet core material: WC-Co
Core hardness: 1450 HV

Figure 2. Characteristics of the billet Nammo AP8

Figure 3. Scanning electron microscope JEOL 5610

The images were recorded at various magnifications, especially the areas where had been ASB, cracks, pores, and where they were traces of melting and mixing of materials [9]. Hardening of the steel plate after penetrating piercing bullets was determined by measuring the Vickers hardness (HV). The fractographic analysis of cracks, that have occurred during the ballistic test, for which it was necessary to break down the samples, has been done to determine the mechanism of formation and spreading of the cracks and localize the nature of the fractured surfaces were ignoring and destroying extracts of the errors and faults at liquid nitrogen temperature.

3. RESULTS

In Figure 4 is the microstructure of the steel PROTAC 500 before the ballistic test. The microstructure consists of tempered martensite, and the hardness of such steel is 540 HV.

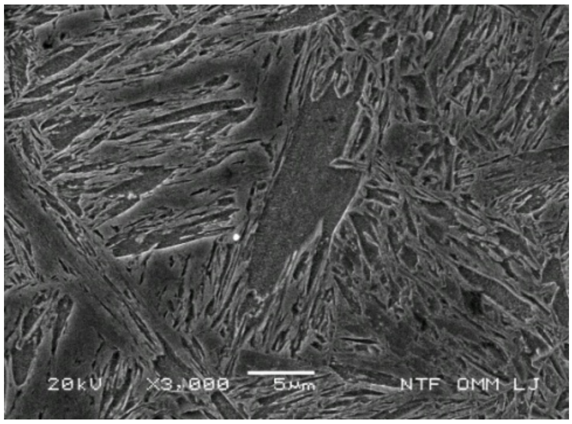


Figure 4. The microstructure of steel PROTAC 500

In Figure 5 (left), there is a front side of the panels PROTAC 500 after ballistics testing with the markings of three samples were cut and prepared for further analysis. All armoured piercing bullets are stopped in the plate. In interpreting, the results of ballistic tests is the most important information if a bullet penetrates the target [6]. In Figure 5 (right), there is the back side of the panel after ballistic test. In none of the shots the perforation of the panel occurred [10].

The testing results and descriptions of the standard VPAM are collected in Table 3.

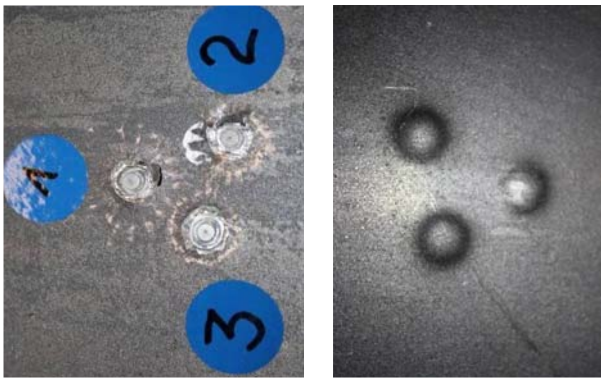


Figure 5. Front (left) and back (right) side of the steel plate PROTAC 500 after ballistic testing – details of three shots

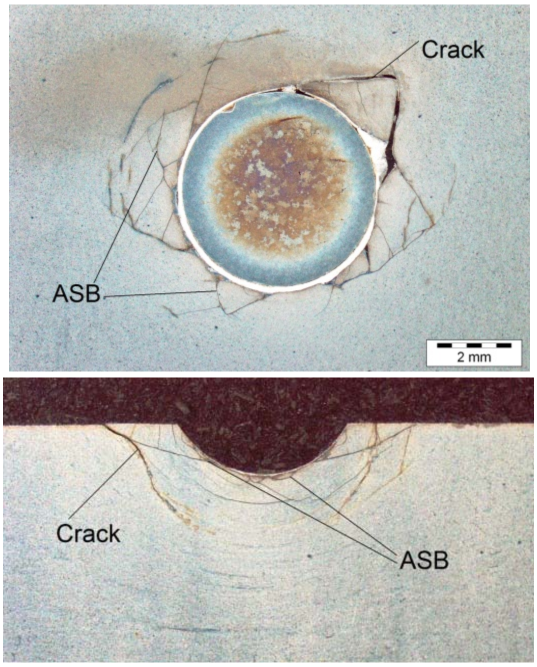
Table 3. Parameters of the ballistic tests and description of the results

	Distance (m)	Shot angle (°)	Impact velocity (m/s)	Bullet energy (J)	Break trough
Sample I	10	90	929	3624.77	No
Sample II	10	90	931	3640.40	No
Sample III	10	90	937	3687.47	No

By the shot to the sample A, the bulge with a crack was formed, that does not transmit light by other shots, but it was smaller bulge without cracks. For a more detailed picture of the interactions between bullets and plate, the samples for metallographic analysis were prepared.

Figure 6 consists of a macro picture of two analytical levels of sample III cross-sections. In Figure 6a, there is a cross-sectional view of the upper level of the sample, where there is a significant number of cracks, and branched adiabatic shear bands which extend from the border between the envelope bullets (bright narrow band around the circumference of the core) and the base material towards the interior of the target. In Figure 6b is a half cross-sectional view of the lower level of the sample. At this level, it is less ASB and cracks at the same time do not go so far into the interior of the target. Most of the kinetic energy of the projectile to the lower level is already spent.

Figure 7 shows the macro-picture breakthroughs balls on the analysis of sample III, giving examples of cracks and ASB. In the area between the ball and the lower edge of the steel plate, they have cracks in the form of a pin. Breakthrough with pin is a common mechanism of penetration through the high strength steels in which the phenomenon of ASB has an important role. The formation of the plug occurs when the thickness of the target is approaching to the diameter of the bullet. Notice also that the bullet after a stoppage due to elastic deformation and the target are slightly separated.



a)
b)

Figure 6. Macroscopic cross-sectional images of the sample 1 (a - upper level, b - lower level)

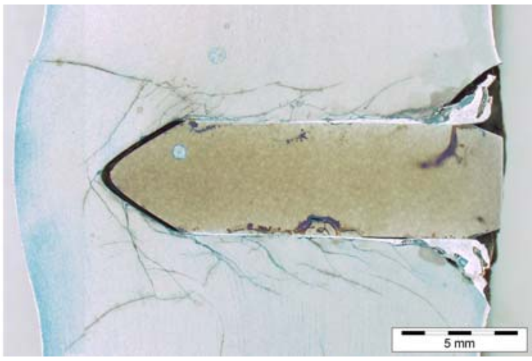


Figure 7. Macroscopic picture of break throughs bullet through the sample III

For the sample III, we have also measured the length of the cracks and ASB. The average length of the cracks on the sample C is 3.9 mm, the average length of the ASB was 4.3 mm, which indicates a very high-speed deformation.

In Figure 8 is transformed ASB, which extends from the edge of penetration (primary ASB) inside the plate (secondary ASB), the medium level of sample I ASB in the investigated steel vary in length, width and branching. Mechanism for the growth and spread of ASB is not a generally accepted criteria, in the literature is generally assumed that the spread and growth of ASB are related dictated to the dynamic recrystallization inside the ASB.

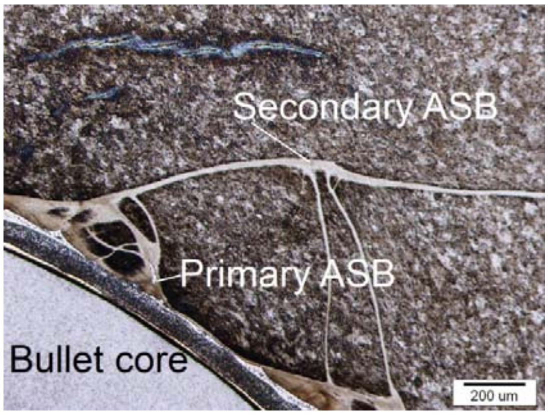


Figure 8. The microstructure of the cross-section of the target at the centre of the bullet. Course of ASB and cracks (sample III)

4. CONCLUSIONS

The research analyzed the ballistic properties of armor steel plate PROTAC 500 against armored piercing bullets caliber 7.62 mm.

The most obvious and significant phenomena in penetrating of the piercing bullets Nammo AP8 in steel plate (target) PROTAC 500 are:

1. strain hardening of steels,
2. the appearance of cracks and local failure,

3. adiabatic shear bands (ASP) and related phase transformations: austenitic, martensitic, melting, solidification, and

4. melting and alloying at the border of the bullet /steel of the plate (target).

5. ACKNOWLEDGEMENT

The authors want to thank professor Ladislav Kosec (University of Ljubljana), dr. Slavko Ažman+ (ACRONI d.o.o.), professor Franc Vodopivec (Institute of Metals and Technology), dr. Milan Rimac (Metallurgical Institute K. Kapetanovic Zenica), and professor Anton Smolej (University of Ljubljana) for mentorship at study armored steels.

The authors want to thank mrs. Nika Breskvar (University of Ljubljana) and mr. Samo Smolej (University of Ljubljana) for SEM analysis, and mr. Matjaž Marčetič (ACRONI d.o.o) for technical support.

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НОВА ГЕНЕРАЦИЈА ПАНЦИРНОГ ЧЕЛИКА

Сажетак: Инжењери твртке PROTAC д.о.о. и највеће словенске жељезаре ACRONI д.о.о. су у сурадњи с домаћим и страним научним институцијама дизајнирали и развили нову генерацију панцирног челика PROTAC 500. Челик PROTAC 500 спада у групу високочврстих нисколегираних челика (HSLA). Овај је челик израђен у жељезари ACRONI д.о.о. стандарним индустријским поступком. Релевантна механичка својства челика постигнута су одговарајућом топлинском обрадом: каљењем и попуштањем. Прелиминарна испитивања механичких својстава челика су показала могућност примјене челика PROTAC 500 за лака оклопна возила. У раду су анализирана балистичка испитивања нове генерације одговарајућих панцирних плоча из челика PROTAC 500 с пробојним мецима калибра 7.62 мм с језгром од волфрамових карбида. Истраживана је и интеракција између панцирног челика и пробојних метака. Најзначајније појаве присутне за вријеме пенетрације пробојних метака Nammo AP8 у челичну мету из челика PROTAC 500 су деформацијско очвршћавање, појава пукотина и локалних оштећења те адијабатски смицајни појасеви (АСП), а везане су с фазним трансформацијама, таљењем као и с легирањем на међупровршини метак/челична плоча.

Кључне ријечи: челик, плоча, противбалистичка заштита, адијабатски смицајни појасеви (АСП).