IETI Transactions on Engineering Research and Practice
http://ieti.net/TERP/

2018, Volume 2, Issue 2, 42-47, DOI 10.6723/TERP.201812_2(2).0006

ARMOUR STEEL PLATES OF NEW GENERATION

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Abstract Co-workers of the biggest Slovenian steel producer ACRONI d.o.o. in cooperation with domestic and foreign institutions of science have been designed and developed a new generation of high quality low alloy steel PROTAC 500 in the form of plate for the armour protection. Steel PROTAC 500 represents a high-quality world-class product. Steel PROTAC 500 has excellent mechanical properties, including standard technological characteristics, such as good tensile properties, excellent impact strength at low temperatures, hardness and deflection as well as ballistic testing where the PROTAC 500 armour plate is made according to the NATO standards as it has lower required thickness of protection in comparison to the competition.

Keywords: Adiabatic shear band (ASB); armour steel; plate; protection.

1. INTRODUCTION

The selection of the appropriate armour material is crucial to ensure the adequate safety and mobility transport systems [1]. When selecting or developing the appropriate materials for the armour 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. With the appropriate production technology, which includes synthesis, melting, continuous casting, hot forming, heat treatment, etc. [2]. High strength low alloy (HSLA) steel of good functional properties at affordable prices can be produced [3].

By improving the strength and toughness of the steel the required thickness and the weight of the steel shell is reduced [4]. Such steels are competitive to other materials for the armour [5]. In the context of this study, we carried out a ballistic test of high strength low alloy steel PROTAC 500, whose mechanical properties and testing conditions are collected in Table 1.

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Table 1. Mechanical properties of steel PROTAC 500 at testing temperature 20 °C.

Yeald strength RP0,2	1200 MPa
Tensile strength Rm	1600 MPa
Elongation A5	8 %
Impact toughness	20 J
Hardness	480 – 530 HB

Steel PROTAC 500 belongs to the group of high strength low alloy (HSLA) steels. It is made in Slovenian steelwork ACRONI 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 armoured vehicles. Ballistic testing was performed by using 7.62 mm armoured 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 [6]. 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) [7]. 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. 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, 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 during the deformation very hot, 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.

The amount of produced PROTAC brandmark steel increases rapidly. Figure 1 shows the amount of manufactured PROTAC 500 semi-products produced by ACRONI d.o.o.during the period from 2010 to 2017.

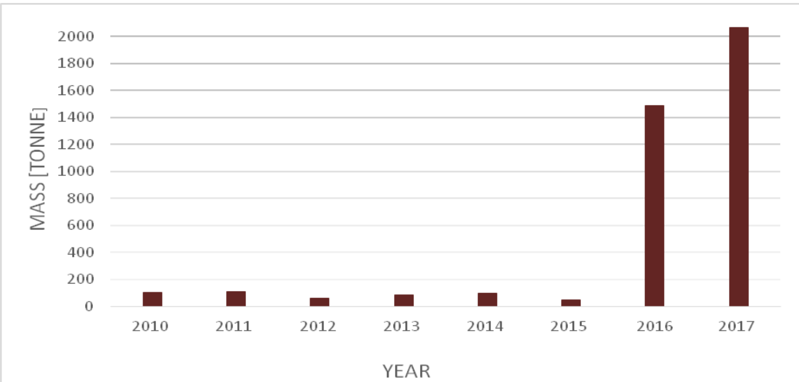

Figure 1. The amount of PROTAC 500 semi-products, produced by Slovenian biggest steel producer ACRONI d.o.o.

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The quantities of steel plates manufactured in years from 2010, when the industrial production of PROTAC 500 steel started, to 2015 were up to a maximum of 100 tons per year. In 2016, production increased to 1487 tonnes, and in 2017 it already exceeded the 2000 tonnes on an annual level.

2. EXPERIMENTAL WORK

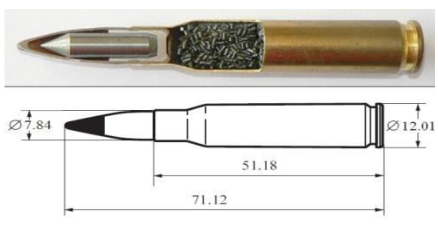
For the ballistics testing a steel PROTAC 500 testing plate with dimensions of 500 x 500 x 20.8 mm was used. Six shots were conducted under the terms of the standard VPAM and STANAG 4569 (Table 2) [7]. Nammo AP8 is the cartridge of an armoured-penetrating bullet caliber 7.62 x 51 mm (.308 Winchester) [7]. American label of the cartridge is the M993. It tends to be used against targets with light armour.

Table 2. Terms of ballistic test according to the standard VPAM and STANAG 4569 [7].

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 armoured piercing of bullets with steel cores. The bullet is made up of a core of tungsten carbide, mounted in an aluminium cup shell is made of steel coated with brass. In Table 3 are collected the properties of the bullet Nammo AP8, and image of transected cartridge and the cartridge sketch with the main dimensions.

Table 3.Characteristics of the billet Nammo AP8 [7].



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

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 were 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. This was followed by analysis with the scanning electron microscope (SEM) JEOL 5610, which allows the observation of microstructure and qualitative and quantitative chemical analysis [8]. The images were recorded at various magnifications, especially the areas where had been ASB, cracks, pores, and where they were traces

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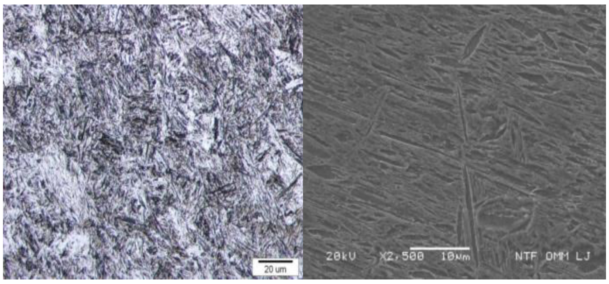
of melting and mixing of materials. Hardening of the steel plate after penetrating piercing bullets was determined by measuring the Vickers hardness (HV). The fractographic analysis of cracks that have occurred during the ballistic test, for which it was necessary to break down the samples have been done. To determine the mechanism of formation and spreading of the cracks and localized the nature of the fractured surfaces were ignoring and destroying extracts of the errors and faults at liquid nitrogen temperature.

3. RESULTS

In Figure 2 is the microstructure of the steel PROTAC 500 before the ballistic test. The microstructure consists of tempered martensite.



a b

Figure 2. The microstructure of steel PROTAC 500; tempered martensite (a - (OM), b - (SEM))

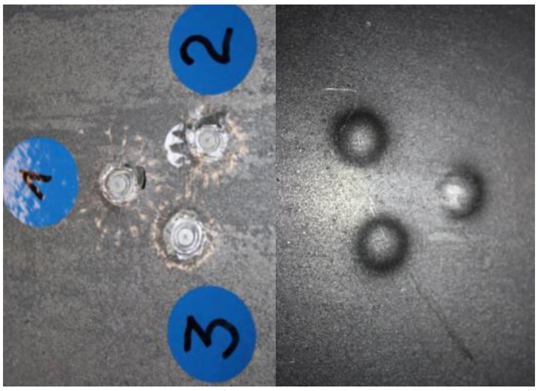


Figure 3. Front (left) and back (right) side of the steel plate PROTAC 500 after ballistic testing – details of 3 shots.

In Figure 3 (left) there is a front side of the panels PROTAC 500 after ballistics testing with the markings of three samples were have 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 [9]. In Figure 3 (right) there is the back side of the panel after ballistic test.

In none of the shots no perforation of the panel occurred. The testing results and descriptions of the standard VPAM are in Table 4.

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Table 4. Parameters of the ballistic tests and description of the results.

	Distance (m)	Shot angle (°)	Impact velocity (m/s)	Bullet energy (J)	Break trough
Sample A	10	90	929	3624.77	No
Sample B	10	90	931	3640.40	No
Sample C	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.

In Figure 4 there is a cross-sectional view of the upper level of the sample A, where there are 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.

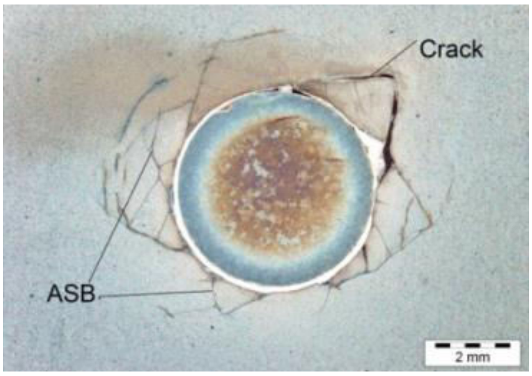

Figure 4. Macroscopic cross-sectional image of the sample A (upper level).

Figure 5 shows the macro-picture breakthroughs balls on the analysis of sample C, giving examples of cracks and ASB.

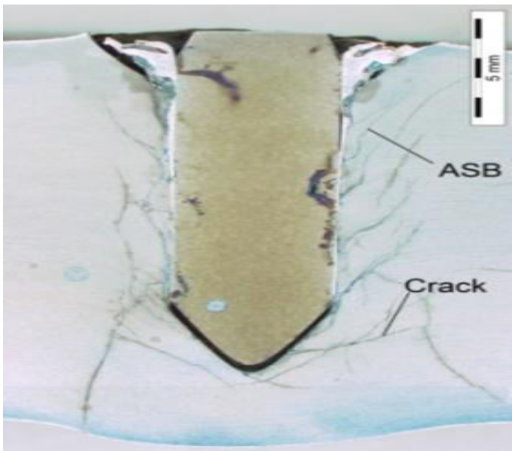

Figure 5. Macroscopic picture of breakthroughs bullet through the sample C, marked as cracks and ASB.

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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. For the sample C 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.

4. CONCLUSIONS

The research analyzed the ballistic properties of armour steel plate PROTAC 500 against armoured 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:

- strain hardening of steels,
- the appearance of cracks and local failure,
- adiabatic shear bands (ASP) and related phase transformations: austenitic, martensitic, melting, solidification, and
- melting and alloying at the border of the bullet /steel of the plate (target).

Acknowledgements

The authors want to thank dr. Slavko Ažman+ (ACRONI d.o.o.), professor Ladislav Kosec (University of Ljubljana), professor Franc Vodopivec (Institute of Metals and Technology), and professor Anton Smolej (University of Ljubljana) for their mentorship at study HSLA steels.

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