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NANOSTRUCTURED BAINITE-AUSTENITE STEEL FOR ARMOURS CONSTRUCTION

NANOSTRUKTURALNE STALE BAINITYCZNO-AUSTENITYCZNE DO ZASTOSOWAŃ W KONSTRUKCJACH OPANCERZENIA

Nanostructured bainite-austenite steels are applied in the armours construction due to their excellent combination of strength and ductility which enables to lower the armour weight and to improve the protection efficiency. Mechanical properties of the bainite-austenite steels can be controlled in the wide range by chemical composition and heat treatment. In the paper the results of investigation comprising measuring of quasi – static mechanical properties, dynamic yield stress and firing tests of bainite-austenite steel NANOS-BA® are presented. Reported results show that the investigated bainite-austenite steel can be used for constructing add-on armour and that the armour fulfils requirements of protection level 2 of STANAG 4569. Obtained reduction in weight of the tested NANOS-BA® plates in comparison with the present solutions is about 30%.

Keywords: nanostructured steel, bainite-austenite steel, armours, mechanical properties

Nanostrukturalne stale bainityczno-austenityczne stosowane do konstrukcji osłon balistycznych ze względu na znakomitą kombinację wytrzymałości i ciągliwości umożliwiają obniżenie masy własnej osłon i podwyższenie ich skuteczności ochronnej. Właściwości mechaniczne stali bainityczno-austenitycznych mogą być kontrolowane w szerokim zakresie poprzez modyfikację składu chemicznego i parametrów obróbki cieplnej. W artykule przedstawiono wyniki badań właściwości mechanicznych wyznaczanych w testach statycznych i dynamicznych oraz wyniki prób przestrzeleniowych. Przedstawione wyniki badań wskazują, że stale bainityczno-austenityczne (NANOS-BA®) mogą zostać wykorzystane do konstrukcji opancerzenia o masie własnej mniejszej o 30% w stosunku do rozwiązań stosowanych obecnie dla wymaganego 2 poziomu ochrony według STANAG 4569.

1. Introduction

The present demands for armoured vehicles tend towards reduction in the mass of armours which would lead to construction of vehicles having better mobility and transportation ability. The directions of armour development are determined also by variety of ammunition types which are used in battlefields. Moreover, a tendency for trials of substitution the steel by ceramics materials is apparent, but advanced steel materials currently under development – of substantially higher mechanical properties than conventional steel grades – indicates that steel can be still used for vehicles protection. In the present paper some chosen properties, microstructure characteristics and the results of firing tests of bainite-austenite steel NANOS-BA® are shown. These results indicate that the plates of 8 mm thickness can be used for application where the protection level 2 according to NATO STANAG 4569 is required.

In order to get the proper material for armours structure containing steel layers it should be realized that a proper combination of various mechanical parameters of steel is crucial for the ballistic efficiency. It is commonly known, that above certain hardness level and at high strength the ballistic efficiency decreases due to the reduction of toughness and ductility [1]. Increasing the ballistic efficiency requires to gain knowledge about the mechanisms of projectile impact on the armour, which are complex because of high strain rate generated in the shield and significant impact energy of the projectile. Due to the above, evaluation of protection ability of material using values determined at low strain rate may only be approximated [2-5]. Nahme and Lach [6] determined quasistatic and dynamic properties of some armour steels (Mars 190, Mars 240 and Mars 300) for high strain rates in the range of $10^{-3} \div 10^{6}$ s^{-1}. They found that after 15% deformation the quasistatic and dynamic (strain rate around 3800 s^{-1}) flow curves of Mars 240 are similar. Specimens of Mars 300 grade dynamically tested at strain rates in the range of 1500-2500 s^{-1} were destroyed after 15-20% of deformation at the stress level about 2500 MPa.

It is generally assumed that the amount of projectile erosion and deformation is depended on the target hardness. However, many studies have demonstrated that the most energy absorbing mechanism in resisting penetration by an armour piercing bullet is the plastic deformation occurring in the target material. The main subject of many research projects was to find the suitable hardness level ensuring the best protection

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ability. Hu et al. [7] showed that more brittle cracking around penetration cavities is observed as the hardness is increased. It is not surprising that the V_{50} ballistic limit velocity of armour plate is lower above certain hardness value and in this case material did not provide better ballistic protection. The authors [7] tested modified rolled homogenous armour steel.

Microstructure of armour steel which influences protection performance of the armour is not included in the material specification. Jena et al. [8] analysed the ballistic performance of low alloy high strength steel plates. It was found that the decrease in the ballistic efficiency is caused by high amount of retained austenite and coarse martensitic structure. The optimum combination of strength, hardness and toughness for good ballistic performance of tempered medium carbon ultra-high strength armour steel was determined by Jena et al. [9]. Maweja and Stumpf [10] established that it is possible to predict the ballistic performance of martensitic armour steels by considering the microstructure and morphology of the phases resulted from combination of chemical composition and heat treatment applied. They found that the lower yield strength to ultimate tensile strength ratio (YS/UTS) indicates a higher resistance to localized yielding upon impact and an improved ballistic perforation resistance.

Present paper is focused on results of firing tests of plates made from nanostructured bainite-austenite steel. The developed parameters of thermo-mechanical and heat treatment of bainite-austenite steel (grade NANOS-BA®), lead to formation of carbide free bainitic structure in final products. The structure is composed of nano-laths of carbide free bainite of high density of dislocations and nano-laths and nano-grains of retained austenite, the volume of which was determined in the range of 15÷25 vol.%. With the use of the developed technology the plates of bainite-austenite steel were produced, characterized by very high strength and good plasticity: tensile strength above 2000 MPa, yield stress above 1300 MPa and total elongation in the static tensile test in the range of 12÷15%. Such level of mechanical properties creates possibility to use bainite-austenite steel for production of shields of improved properties, protecting against projectile firing.

2. Material and experimental procedures

The tested material in the form of plates has been hot rolled and heat treated in HSJ S.A. and ZM Bumar Łabędy S.A., respectively. For the tests of resistance to piercing plates of 400×400×8 mm dimensions were used. Tensile properties of the material were determined in the static test at room temperature (yield stress, tensile strength and percentage elongation) according to the PN-EN ISO 6892-1 standard. Measurements of hardness and impact toughness (Charpy-V, sample dimensions: 10×10×55 mm) at the temperatures of +20°C and -40°C were conducted. Samples for the tensile and impact strength tests were cut out from the plates of 6 mm and 10 mm thickness parallel to the rolling direction, respectively.

Firing tests were performed at Wojskowy Instytut Techniki Pancernej i Samochodowej (Military Institute of Armoured and Automotive Technology) in Sulejówek. Firing tests were performed at 0° obliquity, i.e. targets were normal to the trajectory of the projectile. The ballistic barrels of calibre 7.62 mm and 5.56 mm were used. Specimens were mounted on the rigid stand with the distance from barrel of 10 m. Ammunition 5.56×45 mm M193 and 7.62×39 mm API BZ were used, according to the NATO STANAG 4569 level 1 and 2. For the firing with M193 projectile the ballistic limit V_{50} was determined. The ballistic limit V_{50} is defined as the average velocity of a number of test results with the highest partial penetration velocities (target is not defeated) and an equal number of those with the lowest complete penetration velocities (target is defeated). In the TABLE 1 the chemical composition of bainite-austenite steel which was used for investigation are presented. The plates after hot rolling were cut out to the final dimension and subjected to the heat treatment in order to achieve the suitable microstructure and mechanical properties. The plates were austenitised at 950°C during 30 minutes in protective atmosphere, cooled down in the air to the temperature of 210°C and isothermally annealed during 120 and 144 hours. Previous work [1] showed that isothermal heat treatment at this temperature enables to achieve the good combination of strength and toughness which ensure the maximum ballistic efficiency of the plate of thickness greater than 6 mm.

The hardness measurements over plate surface after heat treatment showed proper and uniform values confirming that the heat treatment was conducted correctly. The hardness mean value was 620 HV10 and 610 HV10 after isothermal heat treatment at 210°C during 120 hours and 144 hours, respectively. The mechanical properties of the plates heat treated at 210°C during 120 hours determined in tensile test were: yield strength 1340 MPa, tensile strength 2050 MPa, percentage elongation 13% and the notched impact toughness (Charpy-V) was: 23 J/cm^2 and 14 J/cm^2 at +20°C and -40°C, respectively. After isothermal heat treatment at the same temperature of 210°C but during 144 hours the mechanical properties were as follows: yield strength 1350 MPa, tensile strength 2030 MPa, percentage elongation 12% and impact toughness 12 J/cm^2 at -40°C. The images of microstructure after the final heat treatment are shown in Fig. 1.

TABLE 1

Chemical composition of bainite-austenite steel (wt. %)

C	Mn	Si	Cr	V	Mo	Ti	Cu	N ppm	O ppm	P	S
0.58	1.95	1.79	1.30	0.090	0.67	0.008	0.12	43±6	7±3	0.010	0.004

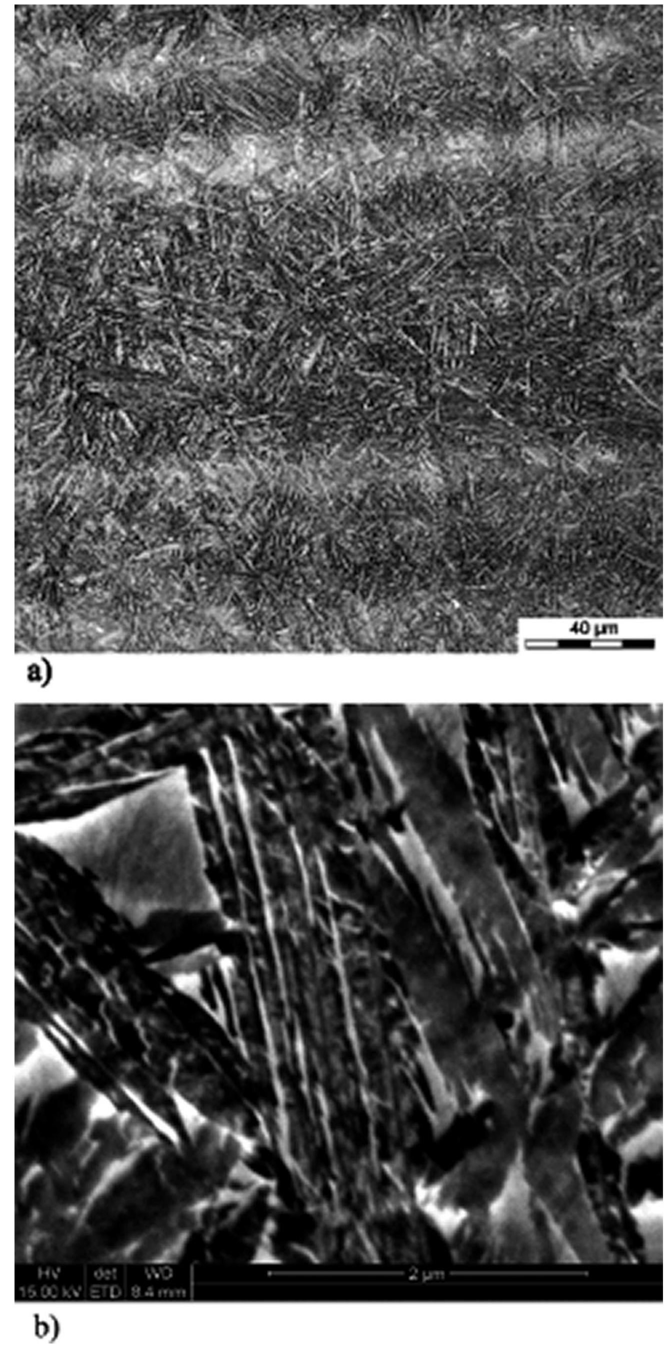

Fig. 1. Microstructure of the test plates of 8 mm thickness after heat treatment at 210°C during 120 hours; a-optical microscopy, b-SEM

The microstructure is typical of nanobainitic steel and is composed of carbide free bainite laths and retained austenite which can be hardly revealed by scanning electron microscopy. The banding seen in Fig. 1a is a result of microsegregation in the solidification process not eliminated entirely during processing of the plates. The microstructure study did not reveal any large inclusions and precipitates which may affect the ballistics efficiency of the plates. The residual austenite content in the samples was 20.4±0.7 (vol.%) and was measured by means of Empyrean X-ray diffractometer. The X-ray analysis was conducted using Co-K_α radiation and beam diameter of 2 mm.

When designing the armours for vehicles its shape should be also taken into consideration because usually it contains curved surfaces and the ability of the material for bending is also crucial parameter for such application, so the bending test of the investigated material after heat treatment was also conducted. The static bending tests at ambient temperature was conducted on the 8 mm thick samples using pin of 35 mm diameter and the distance between the pillars was 80 mm. In Fig. 2, the picture of the sample after bending test is shown.

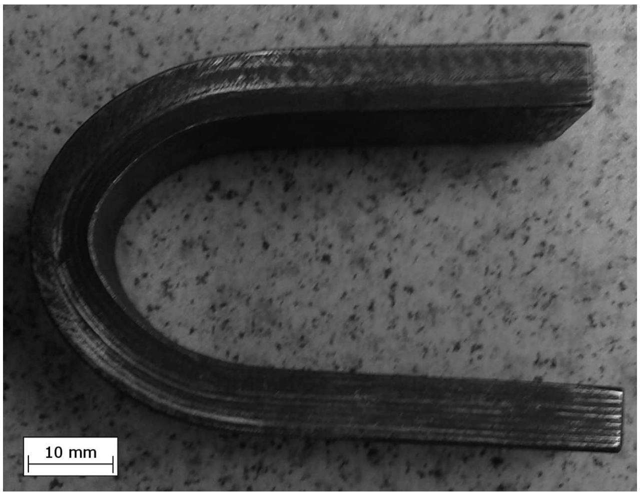

Fig. 2. Picture of the sample from the bainite-austenite steel after bending test

The samples was subjected to bending with angles up to 180° and the investigation of the surface and bulk of the samples did not reveal any cracks.

3. Results and discussion

The plate made from bainite-austenite steel was designed to be used as add-on armour or as insert (for example in vehicle's door). The aim was to achieve the maximum weight reduction in comparison with the presently used martensitic steels. The results of firing are collected in TABLE 2. While testing the ballistic efficiency of the 8 mm thick plate it was necessary to use also the projectiles from level 1 of NATO STANAG 4569 due to its different piercing mechanisms. Our previous investigations [1] showed that the plates of thickness 5-6 mm made from bainite-austenite steel of very high strength are vulnerable for cracking, especially while firing with projectiles of high kinetic energy (for example: 7.62×51 mm NATO Ball characterised by impact energy of 50% greater than 7.62×39 mm API BZ). Therefore our present work was also aimed at checking of cracking resistance during firing with projectile of high impact energy. After accomplishing the firing with 7.62×51 mm NATO Ball we found that the investigated 8 mm plate is able to absorb whole energy of impact without penetration or cracking. Due to the core construction of 5.56×45 mm M193 ammunition and its specific mechanism of penetration this projectile shows higher capability for penetration than 7.62×39 mm API BZ, despite the lower impact energy, thus this projectile was also included for testing. The firing with 7.62×39 mm API BZ projectile showed that 8.0 mm plate made from the bainite-austenite steel after heat treatment at 210°C during 120 hours fulfils the requirements for protection level 2 contained in NATO STANAG 4569. Moreover, one can notice, that this plate withstand the firing with standard 7.62×39 mm API BZ (velocity from STANAG 4569 level 2 is 695 m/s ± 20 m/s). The 8 mm plate after heat treatment at the same temperature but during longer time (144 hours) was pierced. It was an unexpected result due to almost the same mechanical properties as shown above for 120 hours of heat treatment and this requires additional microstructure examination and firing tests.

TABLE 2
Results of firing test of plates made from the bainite-austenite steel of 8 mm thickness

Sample	**Projectile**	**Projectile velocity (m/s)**	**Result** Positive – NOT pierced Negative – pierced
≠ 8.0 mm 210°C/120h	7.62×39 mm API BZ Level 2 of STANAG 4569	736.8	Positive
		746.6	Positive
		763.3	Positive
		766.5	Positive
	5.56×45 mm M193 Level 1 of STANAG 4569	930.7	Positive
		937.0	Positive
		945.5	Positive
		968.6	Positive
		1016.0	Negative
		1035.0	Negative
≠ 8.0 mm 210°C/144h	7.62×39 mm API BZ Level 2 of STANAG 4569	766.8	Negative

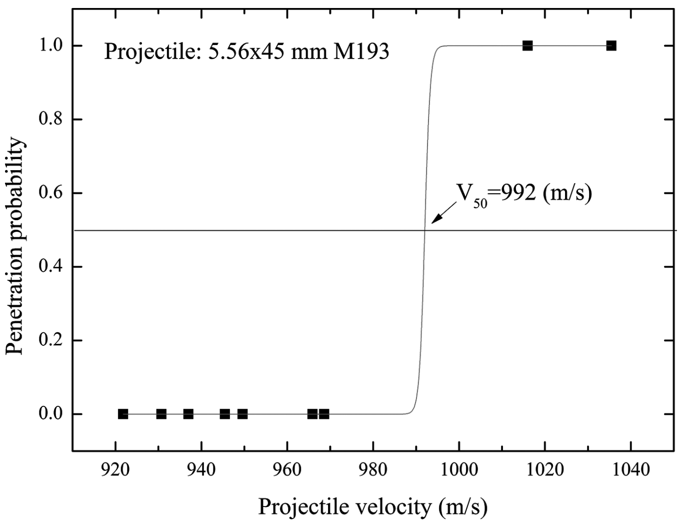

Fig. 3. The diagram of penetration probability vs. projectile velocity for 8 mm plate made from bainite-austenite steel after heat treatment at 210°C during 120 hours

In Fig. 3 the results of the firing using 5.56×45 mm M193 ammunition are shown. The V_{50} determined for 8 mm plate is marked on the diagram. The V_{50} value is about 60 m/s greater than required for level 1 of STANAG 4569. The firing test results using projectiles M193 and API BZ showed that the 8 mm plate withstands firing using standard API BZ projectile but does not withstand standard M193 projectile despite that M193 projectile has lower kinetic energy (M193 – 1798 J; API BZ – 1991 J). This is connected with the different penetration mechanisms due to the core's construction.

For the bainite-austenite steel which was used for the preparation of the plate for add-on armour the dynamic yield stress was also determined. The value of dynamic yield stress gives information about energy which can be absorbed during high energy impact at high strain rate. The investigations of dynamic yield stress was done at Instytut Techniki Uzbrojenia, Wojskowa Akademia Techniczna (Military Academy of Technology in the Institute of Armament Technology) in Warsaw. The results of that investigations showed that the strengthening of this steel grade is proportional to the strain rate and the dynamic yield stress can reach the value of 2600 MPa for the strain rate above 3×10^3 s^{-1}.

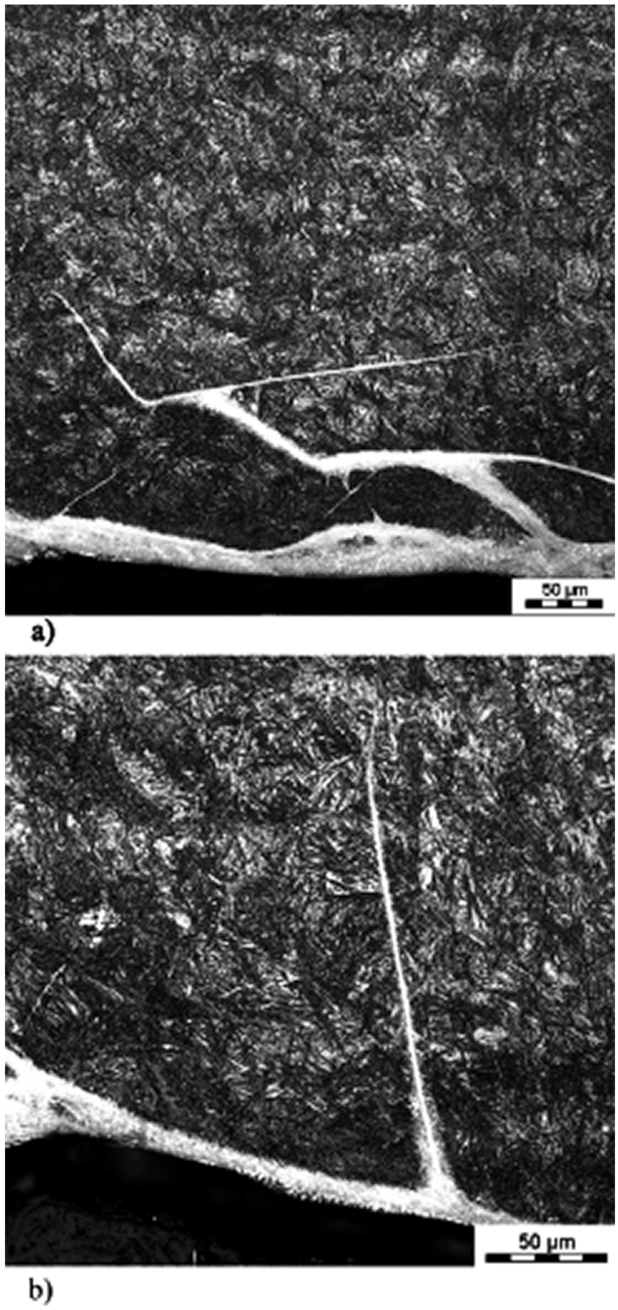

Fig. 4. Microstructure in the area of firing in the plate 8 mm made from the bainite-austenite steel after isothermal heat treatment at 210°C during 120 hours, 7.62×39 mm API BZ projectile

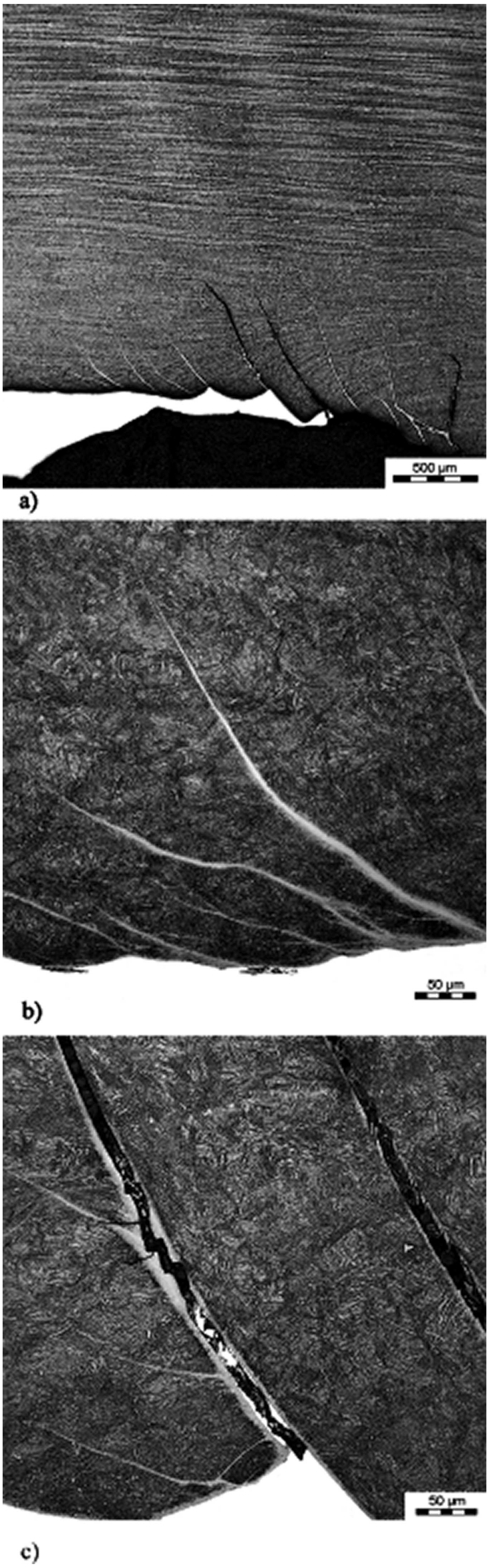

Fig. 5. Microstructure in the area of firing in the plate 8 mm made from the bainite-austenite steel after isothermal heat treatment at 210°C during 120 hours, 5.56×45 mm M193 projectile

Microstructure of the impact area in the 8 mm plate after firing was investigated. In Fig. 4 the images of microstructure of the impact area in the 8 mm plate after firing with API BZ projectile are shown. The occurrence of medium intensity adiabatic shear bands was confirmed in the range of the 200 μm width. Near to the shear bands the micro-cracking was observed but the plate was not cracked even after multihit firing. In Fig. 5 the changes in microstructure in 8 mm plate after firing using M193 projectile are shown. In this case the occurrence of adiabatic shear bands of higher intensity and range about 1 mm width was observed. The micro-cracking was present only inside shear bands and outside deformed area no propagation of cracks was observed. The previous study [1] of 5 mm – 8 mm plate made from the same steel grade and subjected to the firing using AP projectiles, showed that in case of lower impact energy of that projectiles the adiabatic shear bands do not form.

4. Conclusions

The results of the investigations of the 8 mm plate made from the nanostructured bainite-austenite steel showed that it can be used as an add-on armour where protection level 2 according to NATO STANAG 4569 is required. Achieved mass reduction of the armour is about 30% in comparison with the presently used armours base on martensitic steels. The investigated steel grade showed high dynamic yield stress exceeding by 1300 MPa the yield stress measured in static tensile test, therefore the steel with carbide free bainite microstructure shows high capability for dissipation of impact energy. However, the mechanisms of interaction between the plate and the projectile and also the piercing process need further studies which can improve the armours design.

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