PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **10, 4 (38), 2019, 55-70**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

The Process of Increasing the Protective Effectiveness of HARDOX Steel by Way of Selective Thermal and Thermo-Chemical Processing

Andrzej ZIŃCZUK

The State School of Higher Education in Chełm
54 Pocztowa Str., 22-100 Chełm Poland
Author's e-mail address and ORCID:
andrew.zinczuk@gmail.com; https://orcid.org/0000-0003-1853-7044

Received by the editorial staff on 4 April 2018
The reviewed and verified version was received on 11 December 2019

DOI 10.5604/01.3001.0013.6486

Abstract. The work presents the influence of selective thermal and thermo-chemical processing on the protective properties of an example ballistic plate made of HARDOX 500 steel. A novel process that does not require advanced thermal processing appliances and has led to changes in the crystallographic structures in various layers of the material is presented. The presented laboratory and field testing results show that it is possible to achieve a class of ballistic resistance similar to that of thicker plates made of the same steel.
Keywords: metallurgy, ballistic plates, HARDOX

This work has been compiled from the paper presented during the 12th International Armament Conference on Scientific Aspects of Armament & Safety Technology, Jachranka, Poland, September 17-20, 2018

1. INTRODUCTION

Owing to its properties, the steel used to produce ballistic plates is, in many respects, superior to other engineering materials. That notwithstanding, they are still supplanted in many defensive aspects by, for example, ceramic-polymer composites. The most common reason for this is the large mass of iron-carbon alloys. However, reducing the plates' thickness (with the most common values applied being 6 and 8 mm), which would reduce the encumbrance of the people and vehicles being shielded, also entails a simultaneous drop of the ballistic protection class [1]. The solution is to improve certain properties of the steel by way of thermal and/or thermo-chemical processing.

HARDOX steel (presently supplanted by ARMOX and RAMOR steels) is an example of a material belonging to the metal and metal alloy group used in vehicle armour and ballistic fillings of bulletproof vests. However, in light of the literature research conducted, it can be assumed that these steels, uniting the durability and structural characteristics of low-alloy steels meant for improvement by way of thermal processing, as well as the weldability characteristics of increased-durability low-alloy steels, will still constitute a significant part of structural material in the armament industry [1, 2]. Moreover, the research on modifying the properties of this steel do not require a great number of follow-up testing. The reason for this is the existence of numerous scientific works that may constitute a reliable basis for research and comparative material. An analysis of their results allowed the author to optimise some of the operations performed and save time that would be spent on preliminary testing. It is worth noting, however, that the steel that has been the subject of so much research can still be modified in new ways. It is one of the greatest advantages of this type of engineering material.

2. INCREASING THE PROTECTIVE EFFECTIVENESS OF HARDOX 500 STEEL

Within the scope of the work, numerous experiments aiming to increase the ballistic protection degree of armour plates have been conducted. Based on them, a method of thermal and thermo-chemical processing, hitherto not used for reinforcing HARDOX 500, has been developed. In order to confirm the effectiveness of the method, two sets of research materials have been produced. The first one contained metal plates of properties identical or close to those of the steel ballistic bulletproof vest filling available in the market. The other contained plates that have been improved using the designed process. Both sets have been compared for hardness, penetrability, impact energy absorption, and surface deformation. The tests have been conducted using the following devices:

- Czylok FCF 22 HMgo chamber furnace – thermal and thermo-chemical processing;
- SPECTROTEST emission spectrometer – chemical composition analysis;
- ECLIPSE MA 100 metallographic microscope – analysis of the metallographic structures;
- Tukon 2500 micro hardness tester and Rockwell 600 MRD hardness tester – hardness testing;
- Q-2 metallographic sample saw and MoPao 2DE 160 polishing sander – metallographic processing;
- Compact Scan Atos 3D optical scanner – metrological analysis of the surface;
- HT-2402 100 kN universal testing machine – stretch resistance testing;
- SBU 2000 magnetic defectoscope – magnetic particle inspection (Magnetic Testing - MT).

2.1. Preparing the research material

4, 6, and 8 mm thick samples (two per thickness), 260 x 260 mm, were extracted from metal sheets using plasma cutting – the plates were to have a format like that utilised in the ballistic fillings in use. In order to check the output material (as delivered), every sheet was subjected to, i.a.:

- Hardness testing – 15 tests were performed 30 mm apart from one another on the external surfaces and in the cross section;
- Metallographic structure examination – the metallographic microsections of the external surfaces and the cross section were examined;
- Chemical composition analysis – 10 measurements were taken on the external surfaces and after sanding at two depths (0.5 and 0.25 of the thickness of a particular sheet).

The hardness testing and chemical composition analysis results were compared with the values stated by the manufacturer [3] in Table 1 and 2.

Based on the obtained results, it can be concluded that the values measured are significantly lower than those presented in the catalogue, especially those of the surface examinations. This is caused by a great degree of decarbonification and other processes (associated e.g. with the sheet storage method) that may transpire on the surface. This, however, does not explain the growing differences, directly proportional to the sheet's thickness. Based on the available literature, it has been discovered that this was not an isolated case [4, 5]. In order to be able to determine the underlying cause, the manufacturing process (not made known by the manufacturer) would have to be analysed.

Table 1. A comparison between the hardness of the sheets and the values supplied by the manufacturer

HARDOX 500 sheet metal		Average measurement result (HRC)
4 mm sheet	External surfaces	30.2
	Cross section	42.5
6 mm sheet	External surfaces	35.2
	Cross section	44.7
8 mm sheet	External surfaces	44.2
	Cross section	48
Manufacturer's data		48 – 53

Table 2. A comparison between the chemical composition of the sheets and the data supplied by the manufacturer

HARDOX 500 sheet metal		Chemical element content (%)						
		C	Si	Mn	S	Cr	Ni	B
4 mm sheet	External surfaces	0.17	0.23	0.72	0.013	0.68	0.095	0,004
	Sanded-down surfaces	0.19	0.29	1.19	0.009	0.68	0.137	0,004
6 mm sheet	External surfaces	0.20	0.40	1.30	0.010	0.79	0.19	0,004
	Cross section	0.25	0.49	1.57	0.007	0.80	0.20	0,005
8 mm sheet	External surfaces	0.22	0.45	1.50	0.013	1.08	0.18	0,004
	Cross section	0.25	0.50	1.52	0.009	1.08	0.23	0,005
Manufacturer's data (max values)		0,27	0.50	1.60	0.010	1.20	0.250	0.005

2.2. The thermal and thermo-chemical

In order to formulate a reliable assessment of the designed process, the prepared samples were divided into two sets: improved and verification. Every set consisted of three sheets: 4, 6, and 8 mm thick. Both were subjected to normalising annealing at a temperature of 910°C, and an annealing time of 1 h [5].

2.2.1. Preparing the verification set

It has been established that the verification set should be characterised by the same properties as the HARDOX 500 steel currently used for ballistic fillings. To this end, a ballistic plate sold as a ballistic filling for bulletproof vests was examined. Its chemical composition corresponded to that of the prepared samples, and the microscopic examination of the metallographic microsection (Fig. 1), as well as the hardness tests (average value: 49.9 HRC) demonstrated that the thermal processing probably encompassed hardening and low-temperature tempering. Based on this, for each sample from every sheet, appropriate operations were performed as per Table 3 [4, 5].

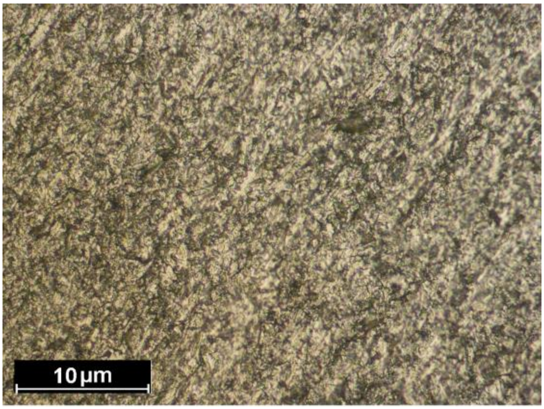

Fig. 1. The metallographic structure of the armoured steel; etched with Nital, zoom 500x

Table 3. Heat treatment of the control plates

Verification set	**Thermal processing (temperature/annealing time)**	
	Hardening (in a 0.1% NaCl solution)	Tempering
4 mm	900°C/0.25 h	temp. 240°C/time 3 h
6 mm	900°C/0.5 h	temp. 240°C/time 3 h
8 mm	900°C/0.75 h	temp. 240°C/time 3 h

2.2.2. Preparing the improved set

Based on the results of the conducted experiments, a thermal and thermo-chemical processing process has been designed. The aim of this operation is to selectively alter the metallographic structures in various layers of the material, leading to achieving greater defensive properties from a ballistic standpoint.

The production process comprised the following operations:

- Layer carburising;
- Selective hardening in ice;
- Selective tempering using the “hot plate” method.

Before carrying out the operation, the surfaces of every plate were sanded. Subsequently, they were placed at the flat bottom of a steel container and covered with the carburising mix (made up of: 96% powdered charcoal, 4% sodium bicarbonate). Thus prepared, the solid carburiser was heated in a furnace at 910°C for 8.5 h. This is the simplest form of the thermo-chemical process that can be performed on steel. Moreover, it allows the effects of the operation on a given surface to be concentrated by way of situating the object the proper way in relation to the powder. The changes to the chemical composition in the carburised layer are presented in Table 4.

Table 4. Chemical composition of the carburized surfaces

HARDOX 500 plate (research set)	**Chemical element content (%)**						
	C	Si	Mn	S	Cr	Ni	B
4 mm	0.51	0.20	1.19	0.01	0.60	0.099	0.004
6 mm	0.49	0.32	1.00	0.01	0.70	0.15	0.005
8 mm	0.48	0.35	1.10	0.01	0.96	0.17	0.005

The first stage of hardening was heating every sample up to 910°C and annealing them for a time appropriate for the verification sets. Subsequently, the samples were cooled by laying the carbonated surfaces on a flat ice surface with a temperature of -9.5°C. This ensured a significant difference in austenite transformation at various sheet depths, which resulted in varied metallographic structures.

The final stage encompassed tempering with the so-called “hot plate” method. This entailed heating the steel priming plate (over 20 mm thick) up to the desired temperature, then placing the flat pieces on it. The samples were kept on the plate with the non-carburised side facing down, until the surface reached a temperature of 200°C. This operation allowed for differences in the diffusional transformation of the residual austenite in the steel’s layers. The processing parameters applied for each of the samples are presented in Table 5.

Table 5. Improved sample tempering parameters

Improved set	**Tempering plate temperature**
4 mm	220°C
6 mm	250°C
8 mm	280°C

2.2.3. Comparison of the sample sets

Both sets were subjected to hardness testing and metallographic microstructure analysis. The examination of the verification samples demonstrated that the changes following thermal processing were present in the entire volume. In the improved set, however, layer structure changes were noted.

Table 6. Comparison of hardness between the two sets

HARDOX 500	Part examined	Measurement average (HRC)
4 mm (normalising)	upper surface	29.2
	lower surface	28
	centre of the section	29.8
4 mm (verification set)	upper surface	44.6
	lower surface	43.9
	centre of the section	45.4
4 mm (improved set)	carburised surface	60.7
	1.5 mm from the carburised surface	47.6
	3 mm from the carburised surface	40
	lower surface	41.1
6 mm (normalising)	upper surface	29.7
	lower surface	27.9
	centre of the section	31.4
6 mm (verification set)	upper surface	45.7
	lower surface	43.5
	centre of the section	44.5
6 mm (improved set)	carburised surface	58.6
	2 mm from the carburised surface	45.6
	4 mm from the carburised surface	40.1
	lower surface	42.6
8 mm (normalising)	upper surface	33.7
	lower surface	31.6
	centre of the section	33.1
8 mm (verification set)	upper surface	48.2
	lower surface	47.5
	centre of the section	46.6
8 mm (improved set)	carburised surface	59.7
	3 mm from the carburised surface	50.2
	6 mm from the carburised surface	40
	lower surface	42.9

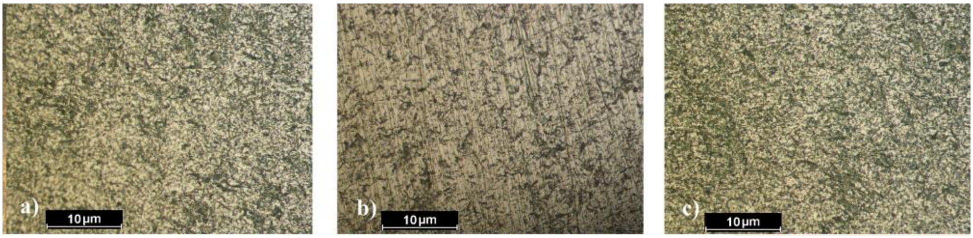

Fig. 2. Metallographic structures of the verification set plates: a) 4 mm, b) 6 mm, c) 8 mm; etched with Nital, zoom 500x

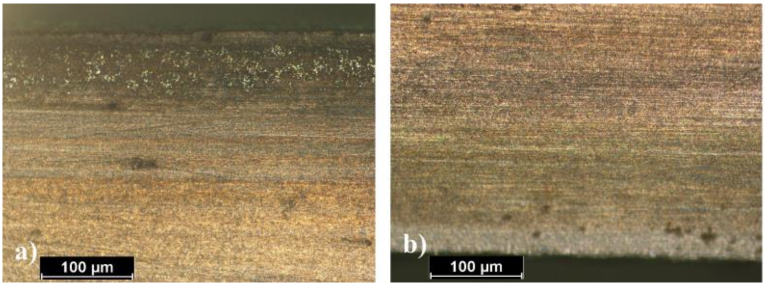

Fig. 3. The metallographic structures of the section of the improved plate, 4 mm: a) upper part (from the carburised surface), b) lower part; etched with Nital, zoom: 50x

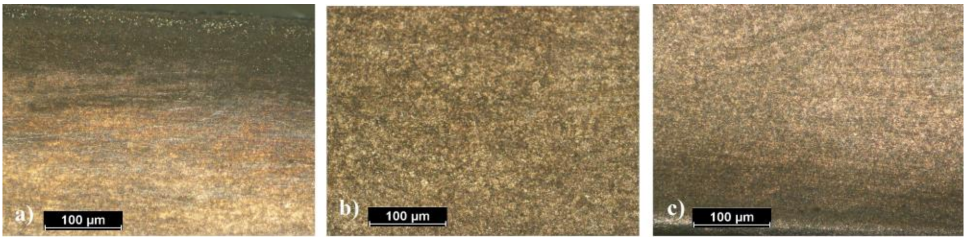

Fig. 4. The metallographic structures of the section of the improved plate, 6 mm: a) upper part (from the carburised surface), b) 4 mm deep from the carburised surface, c) lower part; etched with Nital, zoom: 50x

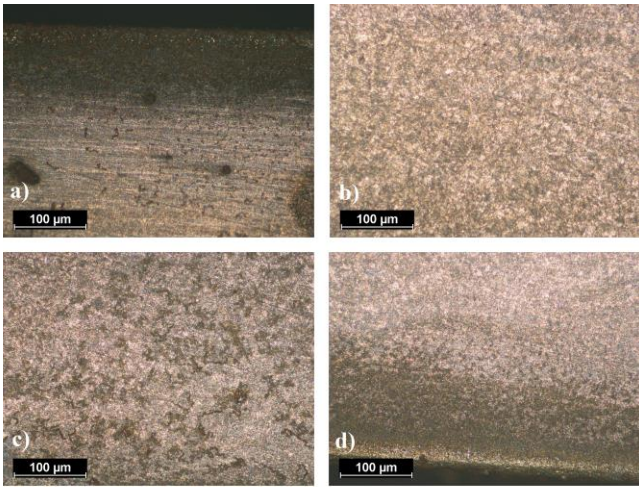

Fig. 5. The metallographic structures of the section of the improved plate, 8 mm: a) upper part (from the carburised surface), b) 3 mm deep from the carburised surface, c) 6 mm deep from the carburised surface, d) lower part; etched with Nital, zoom: 50x

2.3. Ballistic tests of armour plates

Each plate was scanned using an optical measurement device (Atos), then fixed onto clay blocks (approx. 280x280x120 mm in size) with a density like that of the human body, sometimes used in final ballistics testing. The testing encompassed firing shots at each sample from both sets. Every time, the shots were fired in the following order: one 5.56x45 mm round from an AR15 rifle (from 30 m), then two 9x19 mm bullets from a Glock 17 pistol (from 15 m).

The sets made up of the plates and the clay were examined in order to determine the size changes that transpired after the shooting. Due to the author's initial research pertaining to impact force suppression by steel with a "layer structure", the non-carburised side was chosen as the frontal (inlet) surface of the verification set sheets. Most of the attention is dedicated to comparing the 4 mm plate from the improved set with the 6 mm verification plate.

2.3.1. Analysis of the plates after being shot

A preliminary examination demonstrated that only three plates were penetrated or markedly deformed: the 4 and 6 mm verification sheets, and the 4 mm improved set.

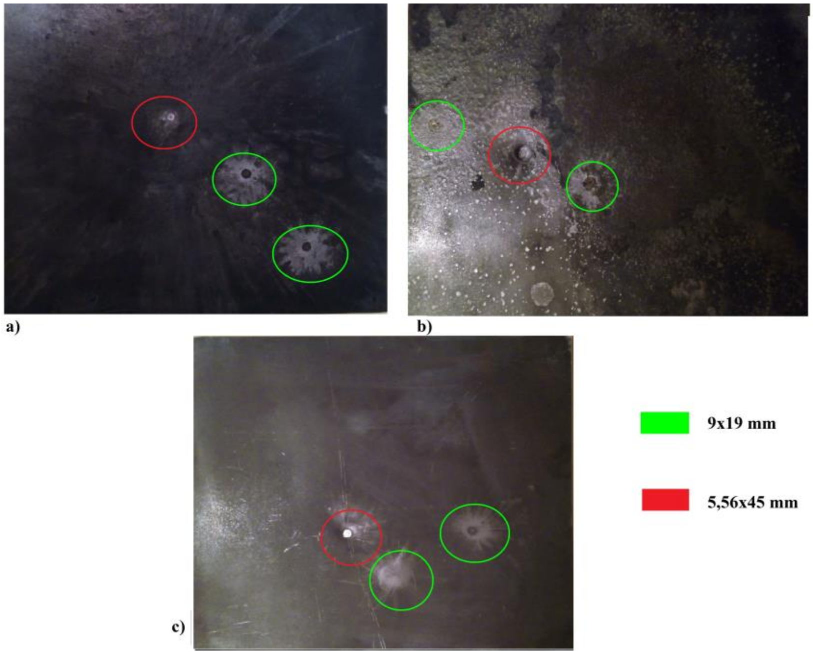

Fig. 6. Verification plates after being shot: a) 8 mm, b) 6 mm, c) 4 mm

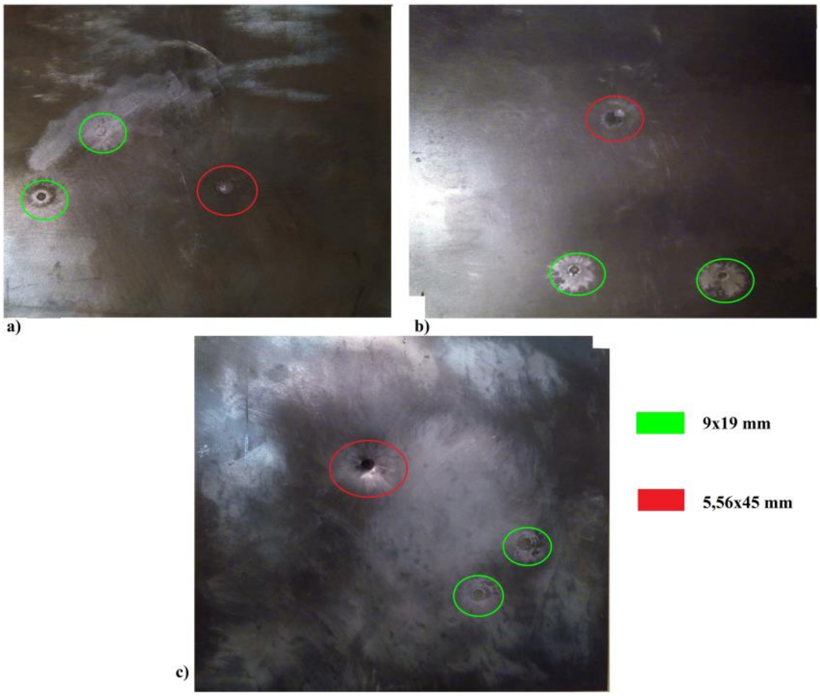

Fig. 7. Improved plates after being shot: a) 8 mm, b) 6 mm, c) 4 mm

The 4 mm plate from the verification set turned out to be the weakest - it was fully penetrated by the 5.56x45 mm, and had the most visible deformation caused by the pistol bullets. In order to demonstrate that thinner metal sheets may possess protective properties similar to their thicker counterparts, the optical scans performed before and after the shooting for the 4 mm plate of the improved set (Fig. 8), and the 6 mm plate of the verification set (Fig. 9) are compared.

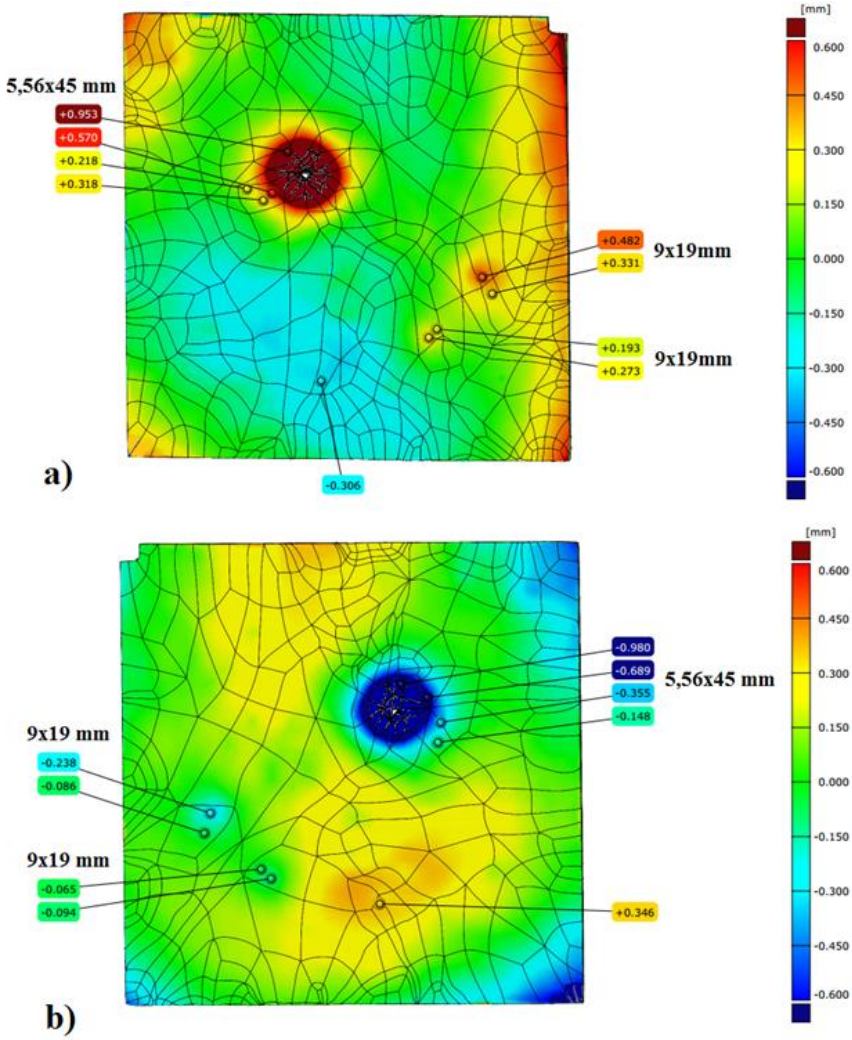

Fig. 8. The analysis of the deformation of the improved 4 mm plate: a) front surface, b) back surface

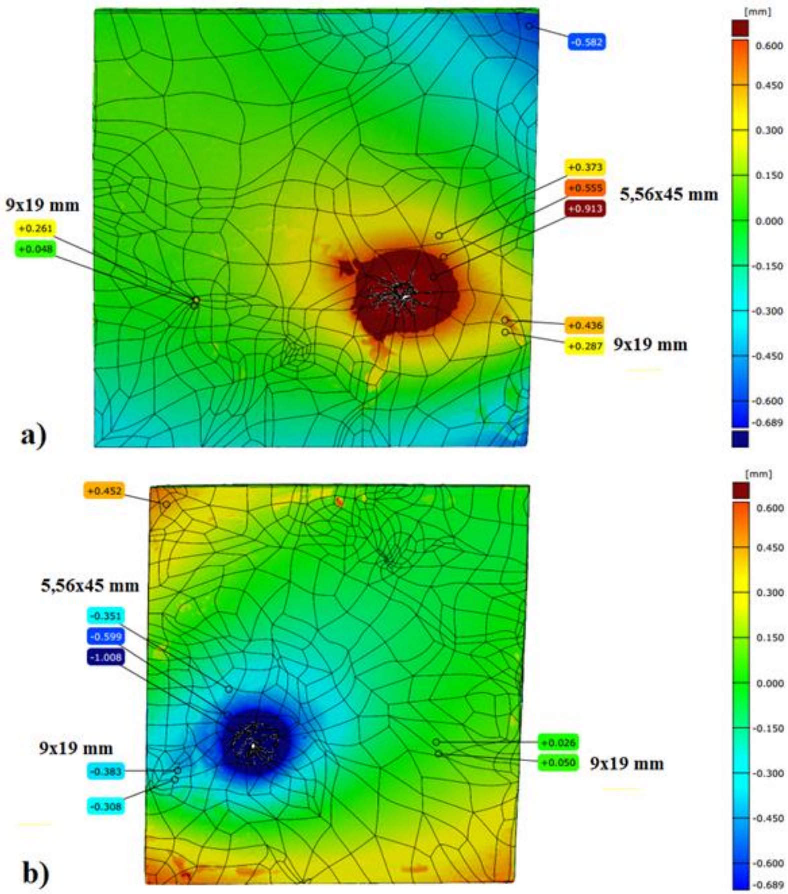

Fig. 9. The analysis of the deformation of the 6 mm plate of the verification set: a)front surface, b) back surface

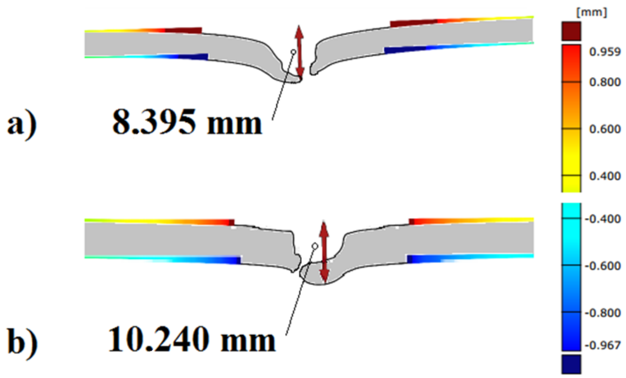

Fig. 10. A section of the deformation caused by a 5.56x45 mm projectile: a) improved 4 mm plate, b) 6 mm verification set plate

The above graphical analyses of the deformations indicate that the process implemented meets the author's assumptions. The sizes of the surface deformations, as well as the comparison of the sections of the deformations caused by the 5.56x45 mm bullets for the improved 4 mm plate and the 6 mm verification set plate are a testament to this. Both plates were damaged to a similar extent (e.g. similar exit hole surfaces), but the extent of the thinner one's deformation was smaller. No micro-cracks appeared on the exit surface either. This is also evidenced by the magnetic particle examination (Fig. 11), which enables the detection of cracks not only on the surface, but also below it.

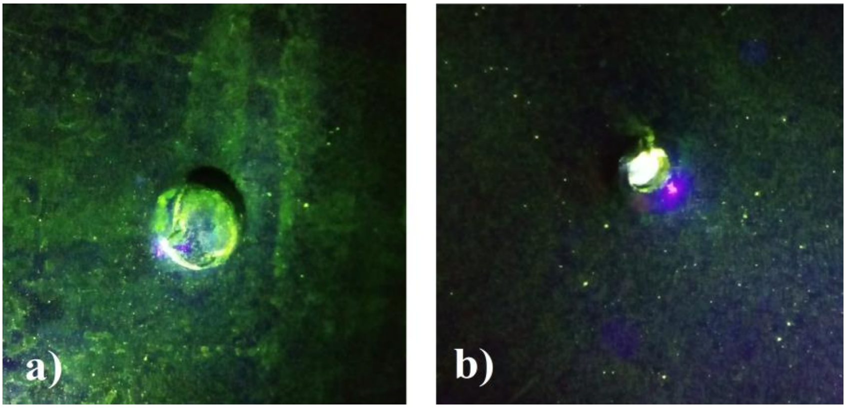

Fig. 11. The results of the magnetic particle examination: a) the 6 mm plate from the verification group, b) improved 4 mm plate

2.3.2. Impact energy absorption

After firing the rounds, the surfaces of the clay blocks were photographed and compared with the initial state (Fig. 12 and 13). Subsequently, in order to determine the sizes of the deformations, modelling plaster castings were made for the purpose of metric determination of the limit values – the measurement results are collected in Table 7.

.

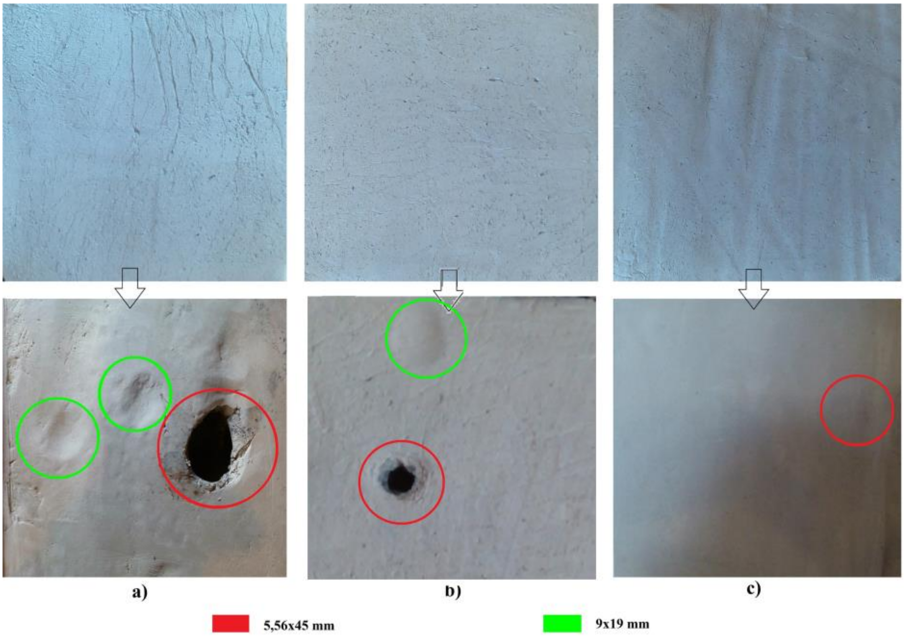

Fig. 12. Clay surfaces pre- and post-shooting for the plates of the verification set:
a) 4 mm, b) 6 mm, c) 8 mm

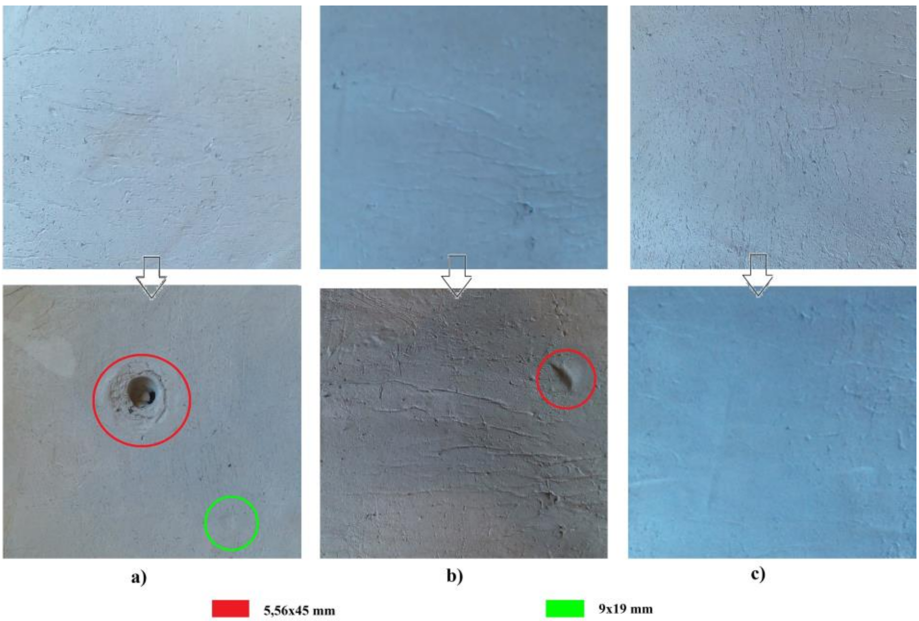

Fig. 13. Clay surfaces pre- and post-shooting for the plates of the improved set:
a) 4 mm, b) 6 mm, c) 8 mm

Table 7. Clay deformation sizes

HARDOX 500 plate	Deforming factor	Dimensions (max diameter/height)
4 mm (verification set)	5.56x45 mm projectile	64.1 mm/83.7 mm
	9x19 mm projectile	45.6 mm/4.3 mm
	9x19 mm projectile	52 mm/5.1 mm
6 mm (verification set)	5.56x45 mm projectile	17.5/15.8 mm
	9x19 mm projectile	43.2 mm/2.5 mm
	9x19 mm projectile	none
8 mm (verification set)	5.56x45 mm projectile	32.2 mm/3.1 mm
	9x19 mm projectile	none
	9x19 mm projectile	none
4 mm (upgraded set)	5.56x45 mm projectile	21.3 mm/21.4 mm
	9x19 mm projectile	18.2 mm/3 mm
	9x19 mm projectile	none
6 mm (improved set)	5.56x45 mm projectile	21.5/5 mm
	9x19 mm projectile	none
	9x19 mm projectile	none
8 mm (improved set)	5.56x45 mm projectile	none
	9x19 mm projectile	none
	9x19 mm projectile	none

Once again, the above tests demonstrate that the assumptions have been met – the deformations of the clay in iterations where the 4 and 6 mm plates of the improved set are close to the thicker verification plates.

3. SUMMARY AND CONCLUSIONS

The obtained results clearly confirm the advantages of using the new HARDOX 500 steel processing process. The presented process requires follow-up research in order to ensure full repeatability. Naturally, many techniques exist that may provide an even greater improvement of its protective properties, such as for example nitrating. However, the presented progression of thermal and thermo-chemical operations is one of the few allowing for structural changes in various layers of the material without using specialised processing equipment.

The work indicates the need to employ detailed research not only at the stage of selecting the chemical composition, but iron alloy shield processing as well. It may result in increasing their protective capabilities without increasing their thickness or introducing alloy additions, and, by extension, improving their performance characteristic without a significant increase in the costs.

FUNDING

All the materials used have been financed entirely by the author. The work made use of the research equipment of the Engineering Studies Centre of the State School of Higher Education in Chełm, Poland.

REFERENCES

[1] Starczewski Lech, Stanisław Szczęch, Dariusz Tudyka. 2010. „Badania stali pancernych w aspekcie ich skuteczności ochronnej". *Prace Instytutu Metalurgii Żelaza* 64 (1) : 110-117.

[2] Dudziński Włodzimierz, Łukasz Konat, Lidia Pękalska, Grzegorz Pękalski. 2006. „Struktury i właściwości stali Hardox 400 i Hardox 500". *Inżynieria Materiałowa* 27 (3) : 139-142.

[3] http://www.ssab.com/ (2018).

[4] Kapcińska-Popowska Dorota. 2011. „Porównawcze badania zużycia ściernego nowej generacji stali Hardox 500 i materiałów powszechnie stosowanych". *Journal of Research and Applications in Agricultural Engineering* 56 (1) : 66-70.

[5] Konat Łukasz. 2007. *Struktury i właściwości stali HARDOX, a ich możliwości aplikacyjne w warunkach zużywania ściernego i obciążeń dynamicznych*. Praca doktorska. Politechnika Wrocławska. Instytut Materiałoznawstwa i Mechaniki Technicznej.

Proces zwiększenia skuteczności ochronnej stali HARDOX za pośrednictwem selektywnej obróbki cieplnej i cieplno-chemicznej

Andrzej ZIŃCZUK

Państwowa Wyższa Szkoła Zawodowa w Chełmie,
Instytut Nauk Technicznych i Lotnictwa
ul. Pocztowa 54, 22-100 Chełm

Streszczenie. W pracy przedstawiono wpływ selektywnej obróbki cieplnej oraz cieplno-chemicznej na właściwości ochronne płyty balistycznej z przykładowej stali HARDOX 500. Zaprezentowano nowatorski proces, nie wymagający zaawansowanych urządzeń obróbki cieplnej, który doprowadził do zmian struktur krystalograficznych w różnych warstwach materiału. Przedstawione wyniki badań laboratoryjnych i terenowych wskazują, iż można osiągnąć zbliżoną klasę odporności balistycznej jaką mają grubsze płyty z tej samej stali.

Słowa kluczowe: metalurgia, płyty balistyczne, HARDOX