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THE INFLUENCE OF THE BAINITIC TRANSFORMATION TEMPERATURE ON PROTECTIVE PROPERTIES OF PASSIVE ARMOURS MADE FROM THE HIGH-CARBON NANOSTRUCTURAL BAINITIC STEEL

Abstract: The results of computer simulation of penetration of the 12.7 mm armour piercing incendiary (API) projectile of the B-32 type into layered armours are presented in this paper. The armours consisted of five variants of the bainitic steel plates (BSPs) with different mechanical properties, obtained as a result of the use of plastic-heat-treatment: bainitic transformation (BT) at different temperatures, rolling at room temperature, different tempering times. The bainitic steel plates of the size 50x50x10 mm were put on the armour steel „witness" plate (Armox 500) of the size 500x500x10 mm. The computer simulations were carried out with the use of the Ansys - Autodyn v12.1.0 program by means of the Lagrange method. Variations of the projectile velocity along the penetration axis of the layered armour (LA) were presented for each variant of the BSPs. After firing of the LA with this projectile the parameters describing deformation of the „witness" plate were compared with the computer simulation results. In case of plates subjected to the bainitic transformation (BT) at the temperatures of 200ºC and 300ºC the result of the computer simulation was similar to the result of the experimental test (respectively: stopping of the projectile, perforation of the BSP and the „witness" plate).

WPŁYW TEMPERATURY PRZEMIANY BAINITYCZNEJ NA WŁAŚCIWOŚCI OCHRONNE PANCERZY PASYWNYCH Z WYSOKOWĘGLOWEJ NANOSTRUKTURALNEJ STALI BAINITYCZNEJ

Streszczenie: W artykule przedstawiono wyniki symulacji komputerowej procesu penetracji pancerzy warstwowych 12,7 mm pociskiem przeciwpancerno-zapalającym (API) typu B-32. Pancerze te zawierały 5 wariantów płytek ze stali bainitycznych (BSPs) o różnych właściwościach wytrzymałościowych, uzyskanych w wyniku zastosowania obróbki cieplno-plastycznej: przemiana bainityczna (BT) w różnej temperaturze, walcowanie w temperaturze pokojowej, odpuszczanie w różnym czasie. Płytki ze stali baintycznych o wymiarach 50x50x10 mm umieszczone były na stalowej płycie pancernej „świadek" (Armox 500) o wymiarach 500x500x10 mm. Symulacje komputerowe wykonano za pomocą programu Autodyn v.12 z użyciem metody Lagrange'a. Dla każdego wariantu płytek bainitycznych przedstawiono przebieg zmian prędkości pocisku wzdłuż osi penetracji pancerza warstwowego (LA). Po ostrzale pancerza warstwowego tym pociskiem porównano parametry odkształcenia płyty świadek z wynikami symulacji komputerowych. W przypadku płytek poddawanych przemianie bainitycznej w 200ºC oraz 300ºC uzyskano wynik symulacji komputerowej zbliżony do wyniku badań eksperymentalnych (odpowiednio: zatrzymanie pocisku, perforację płytki bainitycznej i płyty świadek).

1. Introduction

The armour steels produced commercially achieve the yield strength R_e=1÷1,5 GPa and the tensile strength R_m=1,5÷2 GPa. Theoretical, tensile strength, calculated on the basis of the bonding force is about 10 times higher and amounts to R_m=12÷15 GPa. One of the concepts leading to obtain the high-strength steels is based on reduction of grain size to the level of nanometres. As nanostructural are considered the steels in which the grain size is smaller than 100 nm.

The alternative to the known nanostructural martensitic steels are the high-carbon bainitic steels. The production process of them is more convenient because the bainitic transformation is easier to control than the martensitic transformation. Additionally, the smaller number and mass of alloying elements used for the high-carbon bainitic steels in comparison with the maraging steels decreases cost of their production. The bainitic steels are characterised by lower yield strength and tensile strength in comparison with the maraging steels, but they show higher ductility, what reduces risk of steel brittle fracture under the projectile impact [1÷3].

In this article the authors describe the possibility of the use of plates made from the high-carbon bainitic steel in purpose of the armours construction.

By the temperature of the bainitic transformation control one can directly influence the size of steel grains and the dispersion of carbon. With the decrease of the BT temperature the size of bainitic ferrite plates thickness and particles of carbides decreases, but the number of the particles increases (Fig. 1). The reduction of the bainitic ferrite plate size also increases with the growth of the carbon content in the steel. The decrease of the grain size influences directly the increase of the yield strength and the tensile strength of the steel. The disadvantageous effect of the BT temperature fall is the decrease of the ductility of the steel. The bainitic transformation of the steels at the temperature of 200°C produces the highest tensile strength and yield strength which may exceed 2500 MPa, but their elongation then is low, about 2÷5%. The after-effect is the brittleness of the steels what makes them useless in many applications, requiring transfer of large stress of the material [1÷3].

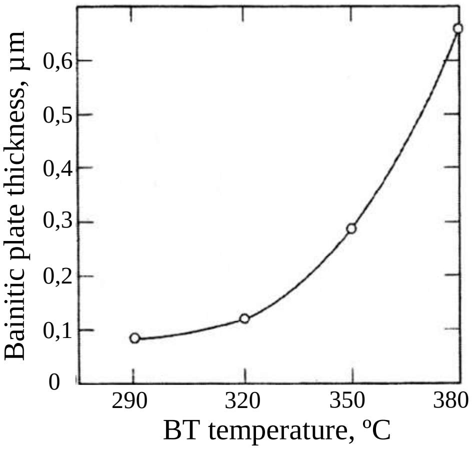


Fig. 1. Dependence of the bainitic plate thickness on the BT temperature [6]

2. Simulations of the 12.7 mm API projectile of the B-32 type penetration into the bainitic steel plates

The numerical simulations of penetration of the 12.7 mm API projectile of the B-32 type into the BSP of the size 50x50x10 mm with the use of the Ansys - Autodyn v12.1.0 program [4, 5] were carried out. The initial velocity of the projectile was 815 m/s which equals the kinetic energy of the impact $E = 16$ kJ. In the simulation there was used the bainitic steel presented in the work [6] and its chemical composition is presented in Table 1.

Table 1. Chemical composition of the bainitic steel plates used in the simulations

Kind of steel	The content of elements, %								
	C	Si	Mn	Mo	Cr	Co	Al	P	S
Sp10	0,79	1,56	1,98	0,24	1,01	1,51	1,01	0,002	0,002

The variants of steel plates subjected to the relevant plastic-heat-treatment, used in the simulations, are shown in Table 2.

Table 2. Parameters of the Johnson-Cook constitutive model for the variants of the BSP

Variant	Kind of steel	*A*, MPa	*B*, GPa	*C*	*n*	*m*
1	Non plastic-heat-treated steel	733	0,5	0,014	0,26	0,87
2	BT at 300ºC for 6 h	800	1,1	0,012	0,3	0,87
3	BT at 200ºC for 72 h	1193	4	0,009	0,5	0,87
4	Rolling in room temperature 0,05ε + tempering at 300ºC for 6 h	1789	7	0,0075	0,9	0,87
5	Rolling in room temperature 0,025ε + tempering at 250ºC for 15 h	2121	9,4	0,0046	1,17	0,87

where: A – yield stress, B – hardening constant, n – hardening exponent, C – strain rate constant, m – thermal softening exponent, ε – strain

The BSPs of the size 50x50x10 mm were put on the steel armour „witness" plate (Armox 500) of the size 500x500x10 mm.

For all materials the Johnson-Cook strength model was used. Only for the steel core of the 12.7 mm projectile of the B-32 type Johnson-Holmquist (J-H) strength model was used. For the Armox 500 armour the parameters of the Johnson-Cook constitutive model were adopted on the basis of literature [7]. Parameters of the strength models for materials used in simulations are shown in Table 3.

Table 3. Parameters of the strength models for the materials used in simulations

No.	Material	Model	*A*, MPa	*B*, GPa	*C*	*n*	*m*	
1	Armox 500	J-C	849	1,34	0,00541	0,0923	0,87	
2	Brass		206	0,505	0,01	0,42	1,68	
3	Lead		24	0,300	0,1	1	1	
4	Steel	J-H	*HEL*, GPa	$A_{J\text{-}H}$	$N_{J\text{-}H}$	$C_{J\text{-}H}$	$B_{J\text{-}H}$	$M_{J\text{-}H}$
			4,478	0,96	0,029	0,21	0,61	0,029

where: HEL – hugoniot elastic limit, $A_{J\text{-}H}$ – intact strength constant, $N_{J\text{-}H}$ – intact strength exponent, $C_{J\text{-}H}$ – strain rate constant, $B_{J\text{-}H}$ – fractured strength constant, $M_{J\text{-}H}$ – fractured strength exponent

The 12.7 mm projectile of the B-32 type used in the simulation is shown in Figure 2. The validation of the projectile model was carried out using information from the literature. According to them the 12.7 mm API projectile of the B-32 type perforates the RHA (*rolled homogenous armour*) of 20 mm thickness [8] without visible projectile deformation. In the work [9] there is the information that the 12.7 mm projectile perforates the 20.7 mm Armox 500 metal sheet.

The numerical simulations of the penetration process of the 12.7 mm API projectile of the B-32 type into the LA containing the BSPs with the use of the Ansys - Autodyn v12.1.0 program are shown in Figures 3÷7.

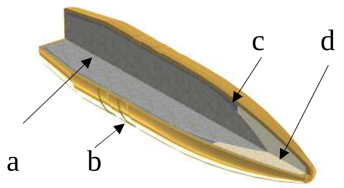


Fig. 2. The 12.7 mm AP incendiary projectile of the B-32 type: a – steel core, b – brass jacket, c – lead can, d – incendiary material

In Figure 3 this projectile perforates the non plastic-heat-treated BSP of 10 mm thickness and the „witness” plate of Armox 500 steel of 10 mm thickness. The velocity of the projectile after the perforation of the bainitic plate and „witness” plate (residual velocity) was 600 m/s (Fig. 8).

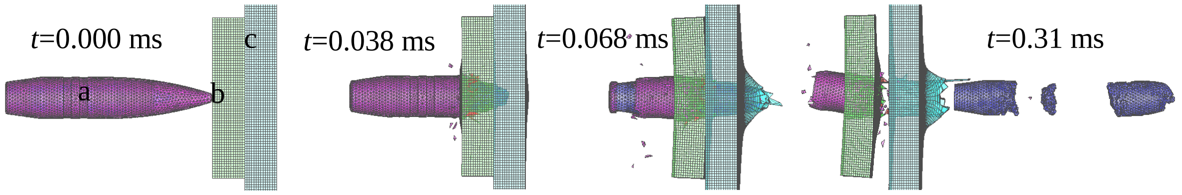


Fig. 3. Simulation of the penetration of the 12.7 mm API projectile of the B-32 type into the non plastic-heat-treated BSP (variant 1): a – the 12.7 mm API projectile of the B-32 type, b – BSP, c –Armox 500

Subjecting steel to the BT at 300°C increases the yield strength of steel from 733 MPa to 800 MPa. Also, in this case the 12.7 mm projectile of the B-32 type perforates the BSP and the „witness” plate of Armox 500 steel of 10 mm thickness (Fig. 4). The velocity of the projectile after the perforation of the bainitic plate and „witness” plate was 550 m/s (Fig. 8).

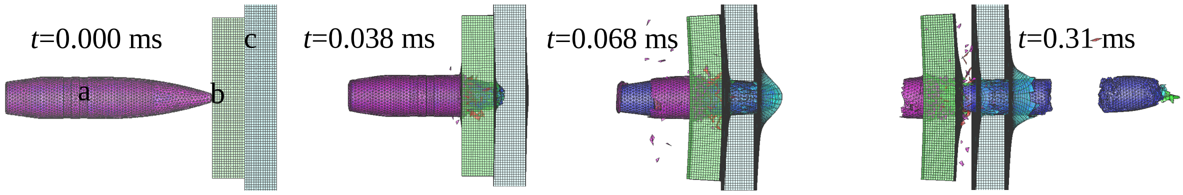


Fig. 4. Simulation of the penetration of the 12.7 mm API projectile of the B-32 type into the steel plate subjected to BT at 300°C for 6 h (variant 2): a – the 12.7 mm API projectile of the B-32 type, b – BSP, c –Armox 500

Subjecting steel to the BT at 200°C increases the yield strength of steel from 733 MPa in the initial state to 1193 MPa after the transformation (approx. 60%). The protective ability of the BSP increased, and projectile penetrated the „witness” plate in the depth of *DP*=9 mm (Fig. 5).

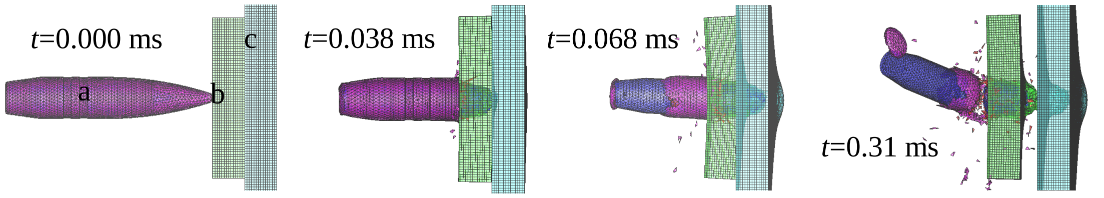


Fig. 5. Simulation of the penetration of the 12.7 mm API projectile of the B-32 type into the steel plate subjected to BT at 200°C for 72 h (variant 3): a – the 12.7 mm API projectile of the B-32 type, b – BSP, c –Armox 500

In the variant 4 the steel was subjected to the BT at 300ºC, rolled at room temperature to achieve the 0,05ε deformation and tempered at 300ºC for 6 h. The yield strength of the steel increased from the initial value 733 MPa to 1789 MPa (approx. 240%) without loss of the ductility. The projectile was stopped on the BSP and did not penetrate the „witness" plate (Fig. 6).

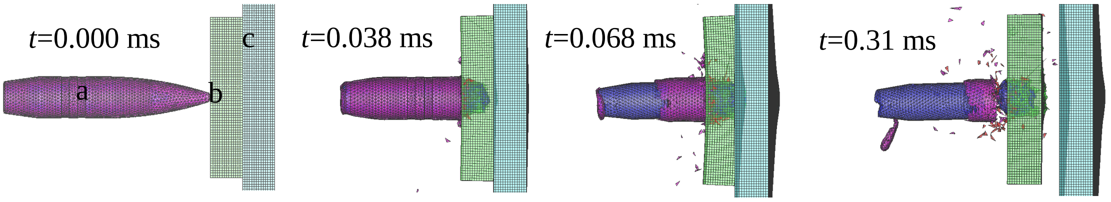


Fig. 6. Simulation of the penetration of the 12.7 mm API projectile of the B-32 type into the steel plate subjected to BT at 300ºC for 72 h, rolled in room temperature and tempered at 300ºC for 72 h (variant 4): a – the 12.7 mm API projectile of the B-32 type, b – BSP, c –Armox 500

In the variant 5 the steel was subjected to the BT at 300ºC, rolled at room temperature to achieve the 0,025ε deformation and tempered at 250ºC for 6 h. The yield strength of the steel increased from the initial value 733 MPa to 2121 MPa (approx. 290%) and the ductility decreased. The projectile in the simulation did not penetrate the „witness" plate (Fig. 7).

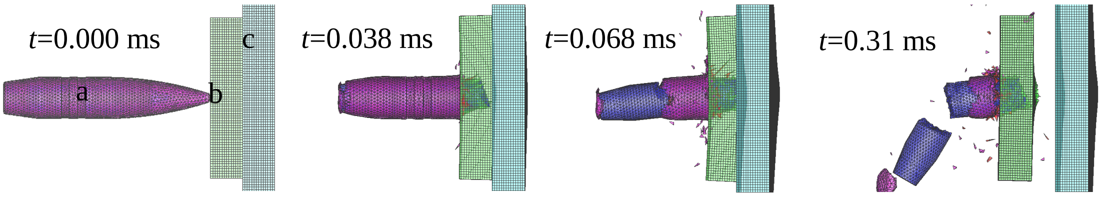


Fig. 7. Simulation of the penetration of the 12.7 mm API projectile of the B-32 type into the steel plate subjected to BT at 300ºC for 72 h, rolled in room temperature and tempered at 250ºC for 72 h (variant 5): a – the 12.7 mm API projectile of the B-32 type, b – BSP, c –Armox 500

In Figure 8 the comparison of the velocity of the projectile in function of time for the simulation of the penetration of the 12.7 mm projectile of the B-32 type the BSP (variants 1÷5) was presented. In variants 1 and 2 the projectile penetrates the BSP and the „witness" plate. The growth of mechanical properties of the steel subjected to the BT at 300ºC for 6 h (variant 2) resulted in reduction of the projectile residual velocity after the perforation both the BSP and the „witness" plate (approx. 550 m/s) in comparison to the variant 1 (approx. 600 m/s). In the simulations of the BSP penetration process (variants 3÷5) the 12.7 mm projectile of the B-32 type did not perforate the „witness" plate.

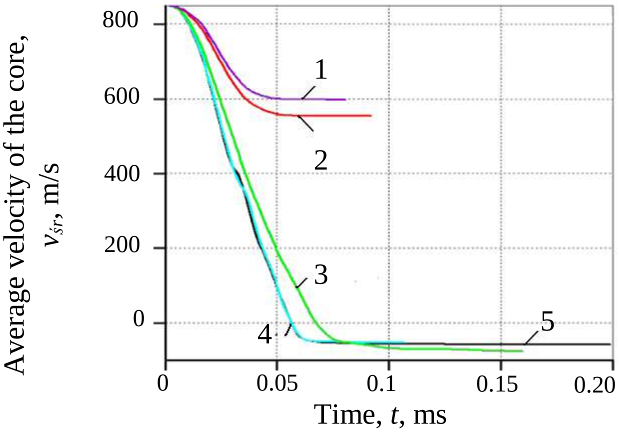
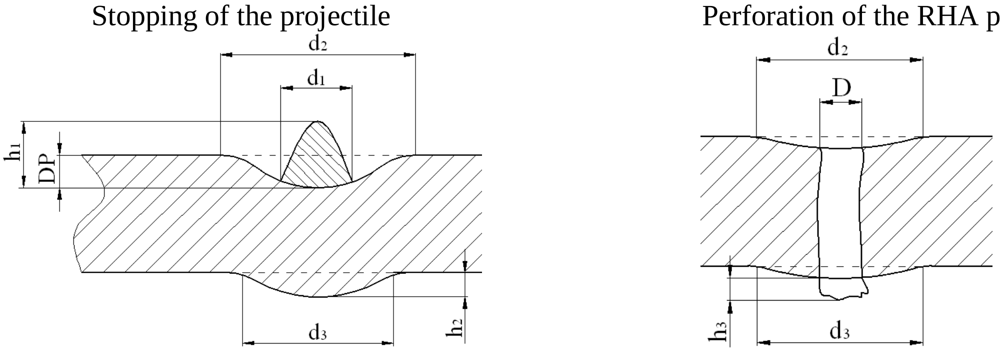


Fig. 8. Velocity of the core of the 12.7 mm API projectile of the B-32 type in the function of time for the simulations: 1÷5 (no. of the BSP variant)

After each of the simulations in the Ansys - Autodyn v12.1.0 program the deformation of the „witness” plate (Fig. 9) was measured in the places where the projectile influences the „witness” plate. The results of these measurements are placed in Table 4.


Stopping of the projectile

Perforation of the RHA plate

Fig. 9. Results of measurements of the deformation of the „witness” plate after the 12.7 mm API projectile of the B-32 type impact: *DP* – depth of penetration/dinge, h_1 – height of hill, d_1 – diameter of hill, d_2 – diameter of dinge, d_3 – diameter of bulge of the back side of the RHA, h_2 – height of bulge of the back side of the RHA, h_3 – height of the back side of the RHA torn off, *D* – diameter of inlet crater of the perforated RHA plate, *d* – diameter of outlet crater of the perforated RHA plate

Table 4. Results of measurements of the deformation of the „witness” plate after the 12.7 mm API projectile of the B 32 type impact

Deformation of the plate, mm	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Depth of penetration/dinge, *DP*	-	-	9	1,5	2,5
Diameter of dinge, d_2	11	16	14,4	30	28
Height of hill, h_1	-	-	-	-	-
Diameter of hill, d_1	-	-			
Height of bulge, h_2			3,5	1,5	1,9
Diameter of bulge, d_3	22	22	32	40	30
Height of back part torn off, h_3	8	7	-	-	-
Diameter of inlet crater, *D*	11	11	-	-	-
Diameter of outlet crater, *d*	11	12	-	-	-

3. Comparison of the simulations results with experiments results

The simulations showed that the steel plate subjected to the BT at 300°C could not protect the „witness” plate against the perforation of the 12.7 mm API projectile of the B-32 type. When the steel plate had been subjected to the transformation at 200°C the projectile did not perforate the „witness” plate.

The confirmation of the correctness of the performed simulations were the experiments in which the plates made from both variants of the bainitic steel behaved in the same way, as in the simulations (Figs. 10, 11).

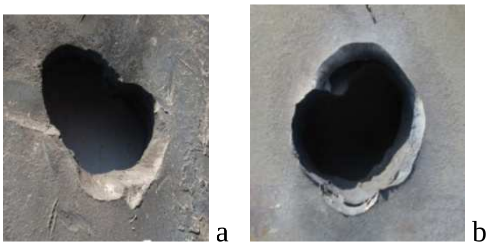


Fig. 10. The „witness” plate protected by the plate made from the steel subjected to the BT at 300°C (variant 2) after being fired: a – the front of the plate, b – the back of the plate

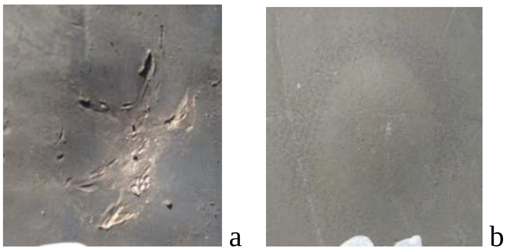


Fig. 11. The „witness” plate protected by the plate made from the steel subjected to the BT at 200°C (variant 5) after being fired: a – the front of the plate, b – the back of the plate

The projectile behaviour was similar in the experiments and in the simulations. The experiments show that the core of 12.7 mm API projectile of the B-32 type does not deform during the impact, and it fragments while meeting a material harder or of the same hardness on its way. Projectile behaved in this simulations in the same way.

Fig. 12. The core of the 12.7 mm API projectile of the B-32 type after being fired at different materials

Table 5 contains results of measurements of the „witness” plate deformation in the places, where the projectile influences the „witness” plate, for the simulations and the experiments.

Table 5. Results of measurements of the „witness” plate deformation in the places where the projectile influences on the „witness” plate, for the simulations and the experiments

Deformation of the plate, mm	Variant 2			Variant 5		
	Simulation	Experiment	Difference, %	Simulation	Experiment	Difference, %
Depth of penetration/dinge, *DP*	-	-	-	2,5	2,5	0
Diameter of dinge, d_2	16	21,2	24	28	26	7
Height of hill, h_1	-	-	-	-	-	-
Height of bulge, h_2	-	-	-	1,9	1,8	5
Diameter of bulge, d_3	22	34,1	35	30	35,2	14
Height of back part torn off, h_3	7	4,3	62	-	-	-
Diameter of inlet crater, D	11	14,8	25	-	-	-
Diameter of outlet crater, d	12	19,8	39	-	-	-

For the plate made from the steel subjected to the BT at 200ºC (variant 5) the results of the simulation and the experiment are close (difference <15%). There is a large difference in the results of the simulation and the experiment (difference 24÷62%) for the plate made from the steel subjected to the BT at 300ºC (variant 2), what testifies about improper parameters of the Johnson-Cook constitutive model, adopted to the simulation.

4. Conclusions

On the basis of the literature analysis and the carried out computer simulations of the penetration of 12.7 mm API projectile of the B-32 type into the BSPs the following conclusions have been drawn:

1. The yield strength R_e=2000÷2500 MPa and the elongation A=5÷15% can be obtained in the high-carbon bainitic steels as a result of the use of suitable plastic-heat-treatment methods.
2. The plate made from the steel subjected to the BT at 200°C protected the „witness” plate against the perforation of the 12.7 mm projectile of the B-32 type.
3. The 12.7 mm projectile of the B-32 type perforated the plate made from the steel subjected to the BT at 300ºC and the „witness” plate.
4. The decrease of the BT temperature from 300ºC to 200ºC results in the reduction of the bainitic steel grain size and the bainitic steel plates thickness (300÷500%), what brings on the increase of the yield strength of the steel to 290%.
5. The close results of measurements of the deformation, in places where the projectile influences the „witness” plate, were obtained both for the simulation and the experiment (difference <15%) for the plate made from the steel subjected to the bainitic transformation at 200ºC (variant 5).
6. The results of measurements of the deformation in places where the projectile influences the „witness” plate for the plate made from the steel subjected to the bainitic transformation at 300ºC (variant 2) were different for the simulation and experiment (difference 24÷62%), what testifies about improper parameters of the Johnson-Cook constitutive model, adopted to the simulation.

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