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Ultrahigh-Strength Nanostructured Steels for Armours*

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Abstract. The paper presents principles of designing and examination results of super-clean high-strength new generation maraging steel for composite armours protecting against piercing with small-calibre armour-piercing (AP) projectiles. The research concerns maraging steel of yield strength ≥ 2,5 GPa and suitable toughness required to achieve high resistance of armour to piercing with AP projectiles. Three base compositions of maraging steel (MS) of yield strength 400 ksi, 500 ksi and 550 ksi with different content of alloying elements Fe, Ni, Co, Mo, W, V are described. The process of vacuum melting of the concerned steels was presented as well as further processing, i.e. homogenizing treatment, hot working, machining, solution treatment, ageing and grinding in order to prepare plates with dimensions of 50 × 50 × 10 mm. The manner of perpendicular firing at the aforementioned plates placed on a stand with RHA armour "witness" plate is presented. Moreover, demonstrated are also the visible results of maraging plates firing with 12,7 mm B-32 type armour-piercing incendiary projectiles on RHA plates. Also shown are the images of scans performed using an electron microscope of maraging plates' fracture surface generated by firing.
Keywords: passive armour, penetration of steel, maraging steel

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1. INTRODUCTION

Institute for Ferrous Metallurgy (IFM) in Gliwice, Poland and Military Institute of Armament Technology (MIAT) in Zielonka, Poland jointly realize the project under EU Operating Programme Innovative Economy, entitled *"Technology of production of superhard nanostructural Fe-based alloys and their application in passive and passive-reactive armours"*. The project is aimed at development of innovative iron-based materials of nano-crystalline structure for construction of layered composite armours used in protection against piercing with small-calibre armour-piercing (AP) projectiles and for other special applications, as well as development of the structure and demo models of armours containing layers of nano-crystalline iron-based alloy materials.

Conventionally, the structure is called "nano-grained" (nano-crystalline) when the size of grains or other basic structure components is smaller than 100 nm, though other limits are also indicated, e.g. Gleiter indicates the range 1÷10 nm [1] as the range of crystallite size in nanostructures. The main advantage of nano-crystalline alloys is very high-strength and crack resistance sufficient for specific applications. Research on ultrahigh-strength steels and Fe alloys implies that, in case of approaching the yield strength of $R_e \approx 3{,}5$ GPa, toughness or ductility is reduced to the level close to zero. In view of this, the fundamental challenge remains of the development of methods for increasing the ductility of nano-structured steels [2].

Mechanisms of projectile impact on armour are complex because of the high strain rate and significant impact energy. Due to the above, characteristics of protection ability of a material by means of values determined in static measurements or at low rate strain may only be approximate [3, 4]. At present, computer simulations of processes occurring during projectile impact on the armour are used in theoretical analysis of protection ability of armour.

It is planned that in the project carried out by IFM and MIAT the following iron-based materials will be manufactured:

- super-clean ultrahigh-strength new generation maraging steel
- high-carbon bainitic nano-crystalline steel
- two-phase nano-crystalline amorphous steel.

The paper contains results of designing and manufacturing at the Institute for Ferrous Metallurgy of the first batch of materials made from the new generation maraging steel as well as conducting tests of firing at plates of these materials at the Military Institute of Armament Technology.

2. PRINCIPLES CONCERNING DEVELOPMENT OF NEW GENERATION MARAGING STEEL

Maraging steels were implemented into industrial production in the 60's of the XX century in the USA and therefore conventional grades of maraging steel are marked with MS letters (**M**araging **S**teel) and succeeding numbers indicating the nominal value of yield strength in stress units used in the USA: ksi, i.e. 1000 pounds per square inch (1 ksi = 6,9 MPa). At present, chemical composition of maraging steel manufactured on the industrial scale is based on the system Fe-18%Ni-Co-Mo-Ti or/and Al, while the yield strength is R_e = 1400÷2400 MPa.

The paper presents the manner of designing the chemical composition and manufacturing technology of such grade of steel, which following application of the optimum heat treatment would achieve a yield strength ≥ 2,5 GPa and maintain a toughness level guaranteeing high resistance to piercing. Therefore, it is planned to achieve the minimum yield strength increased by 1,0 GPa (by 66%) than the maximum yield strength achieved for quenched and tempered armour plates of alloy steels. Achievement of a yield strength ≥ 2,5 GPa and simultaneously proper toughness, requires designing the melting and casting technology of very pure steel in terms of non-metallic inclusions and residual elements content. A dominant mechanism of maraging steel strengthening is precipitation of intermetallic phases' particles of the size of nanometres. As a result of nano-particles precipitation, the influence of grains boundaries and sub-boundaries as well as dislocation patterns on strengthening is declining (Fig. 1).

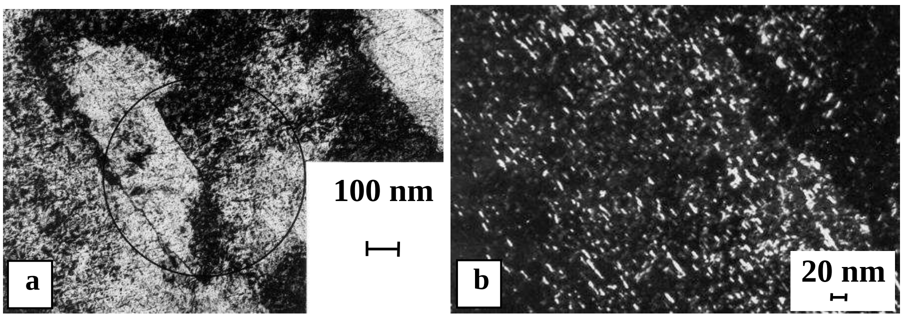


Fig. 1. Precipitations of intermetallic phases' nano-particles in maraging steel, observed by means of transmission electron microscope on thin foil: a – image in bright field, b – image of strengthening nano-particles in dark field

3. PREPARATION OF MARAGING STEEL PLATES

The following base compositions of ultrahigh-strength maraging steels, grades: 400 ksi, 500 ksi and 550 ksi were designed (all chemical compositions given in mass %):

- base composition of MS400 grade: Fe-13%Ni-15%Co-5%Mo-3%W-2%V (total of alloying elements 38%)
- base composition of MS500 grade: Fe-10%Ni-18%Co-5%Mo-5%W-4%V (total of alloying elements 42%)
- base composition of MS550 grade: Fe-8%Ni-20%Co-5%Mo-5%W-4%V (total of alloying elements 42%).

Manufacturing of products from ultrahigh-strength maraging steel with a high crack resistance after final heat treatment, apart from the optimum selection of alloying elements constituting the matrix and forming nano-precipitations of strengthening phases, requires the achievement of high metallurgical purity of the steel, i.e. the lowest possible content of impurity elements S, P and O, interstitial elements C and N as well as residual elements which may have a negative impact on crack resistance, i.e. Si, Mn, Cr and Cu.

The heats of experimental steels were conducted in a VSG 100S vacuum induction furnace having a melting pot with a 100 kg capacity and cast in a vacuum to a cast-iron mould. Ingots were subject to heat treatment homogenizing the chemical composition followed by mechanical surface scarfing. Subsequently, hot plastic working was carried out in order to obtain semis in form of flat bars with a cross section of 13 × 65 mm, the samples of which were prepared (by means of machining methods) for final heat treatment consisting of: solution treatment, quenching from austenite stability range and ageing with various parameters.

Following final heat treatment, samples assigned for firing were grinded, to obtain the dimensions of 50(±0,5) × 50(±0,5) × 10(±0,1) mm. Examples of curves showing the relation between hardness and ageing parameters for MS550 steel, following solution treatment and quenching from the temperature of 900ºC are presented in Figure 2.

Plates of various hardness and microstructure were prepared for testing the resistance to piercing with 12,7 mm AP projectiles: after solution treatment without ageing, after short-time ageing, after three-hour long ageing and after 30 hour-long ageing. Denotation of plates for piercing resistance testing as well as results of plates hardness measurements, as the average of four measurements on the plate surface at the corners, are presented in Table 1.

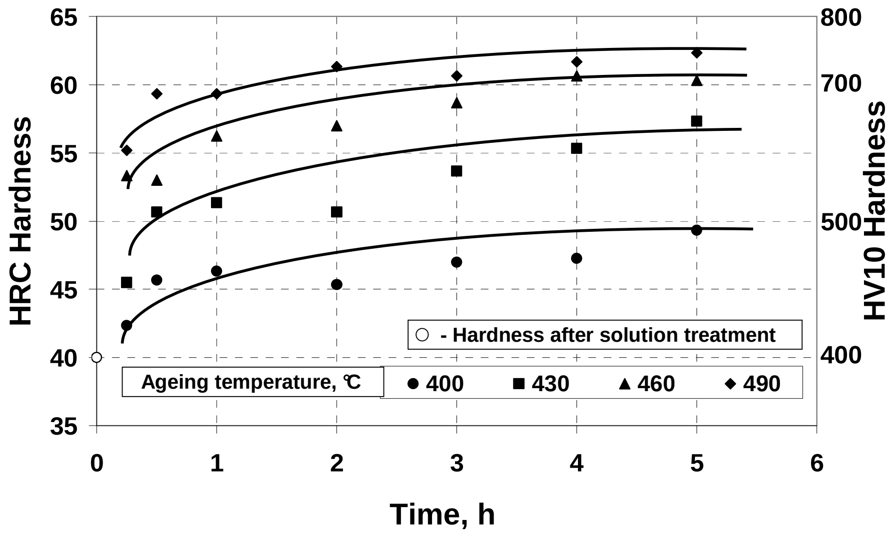


Fig. 2. Ageing curves for steel no. 3 (MS550 grade)

Table 1. Denotations of samples for tests of protection ability and results of hardness measurements

Sample denotation* (shot number)	HRC (HV10) hardness	Sample denotation* (shot number)	HRC (HV10) hardness
1/ 1 (1)	30 (330)	1/ 49/3/1 (13)	58 (640)
1/ 2	31 (340)	1/ 49/3/2 (8)	58 (640)
1/ 3	31 (340)	1/ 49/3/3	57 (630)
2/ 1 (2)	36 (380)	2/ 49/3/1 (14)	61 (700)
2/ 2	36 (380)	2/ 49/3/2 (7)	61 (700)
2/ 3	37 (385)	2/ 49/3/3	61 (700)
3/ 1	38 (385)	3/ 49/3/1 (15)	61 (700)
3/ 2	38 (385)	3/ 49/3/2 (6)	61 (700)
3/ 3	38 (385)	3/ 49/3/3	61 (700)
1/ 43/0.5/1	48 (470)	1/ 49/30/1 (5)	59 (670)
1/ 43/0.5/2	48 (470)	1/ 49/30/2 (12)	60 (690)
1/ 43/0.5/3	49 (480)	1/ 49/30/3	60 (690)
2/ 43/0.5/1	50 (475)	2/ 49/30/1 (4)	64 (780)
2/ 43/0.5/2 (16)	49 (470)	2/ 49/30/2 (11)	64 (780)
2/ 43/0.5/3	50 (475)	2/ 49/30/3	64 (780)
3/ 43/0.5/1	48 (485)	3/ 49/30/1 (3)	64 (780)
3/ 43/0.5/2 (9)	48 (485)	3/ 49/30/2 (10)	64 (780)
3/ 43/0.5/3	47 (480)	3/ 49/30/3	64 (780)

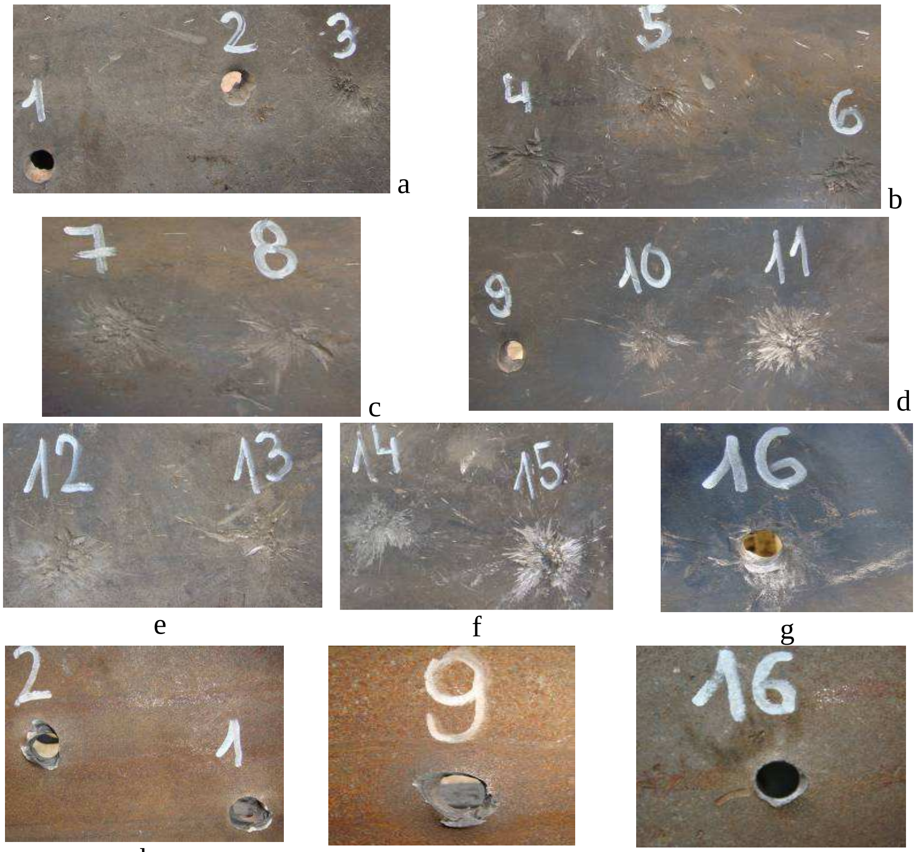
* The first digit of denotation indicates steel grade, while the following – type of heat treatment
1 – MS400 grade maraging steel,
2 – MS500 grade maraging steel,
3 – MS550 grade maraging steel.

4. TESTS OF PROTECTION ABILITY OF MARAGING STEEL PLATES

Plates of experimental maraging steels manufactured using the methods depicted in chapter 3 were subject to firing of 12,7 mm type B-32 projectiles with a velocity of V = 817,5 m/s. The RHA armour "witness" plate with the dimensions of 1000 × 600 × 10 mm, was installed on a stationary stand while the maraging steel plate with the dimensions of 50 × 50 × 10 mm was attached to the previous plate. Firing was executed from a distance of 3 m, at an angle of $\alpha = 0^o$ from the normal to the plate plane (Fig. 3).

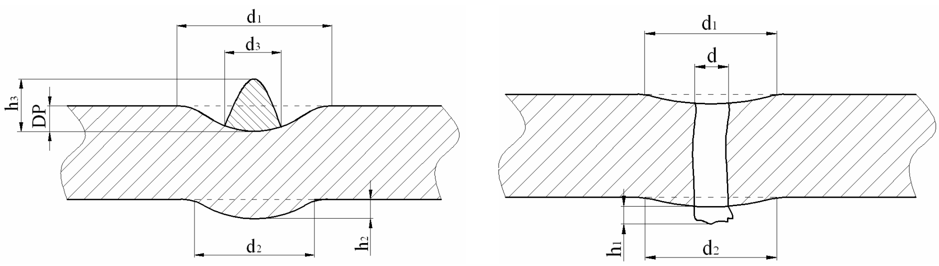
Fig. 3. Stand for tests of protection ability of maraging steel plates placed on an RHA witness plate

View of the results of maraging steel plates firing observed on an RHA armour witness plate is presented in Figure 4, while parameters of interaction effects on the RHA witness plate were measured according to Figure 5.



a b c d e f g h i j

Fig. 4. Results of firing visible on the RHA witness plate after firing with 12,7 mm type B-32 projectiles: a÷g – frontal view, h÷j – back view



a b

Fig. 5. Parameters measured on the RHA witness plate: a – after stopping a projectile, b – after perforation by projectile

Table 2 presents the measured parameters of interaction effects on RHA witness plate after maraging steel plates firing. Piercing of the RHA witness plate:

– occurred in four cases – shots no.: 1, 2, 9 and 16. Examples of maraging plates subjected to firing and morphologies of their fracture as images from electron scanning microscope are presented in Figures 6 and 7.

1 2

Fig. 6. Frontal view of maraging plates (shot no. 1 and 2) following firing with 12,7 mm type B-32 AP projectile

Table 2. Results of tests and measurements of interaction effects on RHA witness plates after firing with 12,7 mm type B-32 projectiles

Shot no.	Penetration depth RHA, DP, mm	Height of			Diameter of				
		tear, h_1, mm	bulge, h_2, mm	lump, h_3, mm	crater, d_1, mm	bulge, d_2, mm	lump, d_3, mm	hole, $d_{max/min}$, mm	
1	piercing	6.5	-	-	22.0	31.5	-	13.0	11.3
2	piercing	8.5	-	-	21.5	28.8	-	14.0	12.9
3	0.6	-	0.9	-	25.6	32.0	-	-	-
4	1.3	-	0.8	-	29.4	34.5	-	-	-
5	0.7	-	1.0	-	31.6	32.1	-	-	-
6	1.3	-	0.5	-	29.8	33.5	-	-	-
7	0.5	-	2.0	-	28.4	37.8	-	-	-
8	0.9	-	1.5	-	32.0	33.9	-	-	-
9	piercing	5.3	-	-	31.9	30.6	-	13.8	11.5
10	0.5	-	0.8	-	34.0	33.7	-	-	-
11	0.8	-	0.7	2.2	34.0	34.1	11.2	-	-
12	0.7	-	1.0	-	33.0	30.0	-	-	-
13	0.5	-	1.4	-	31.9	30.0	-	-	-
14	0.9	-	1.3	-	33.2	36.0	-	-	-
15	1	-	1.5	3.2	39.7	33.0	19.6	-	-
16	piercing	2.7	-	-	25.9	27.5	-	15.0	11.1

– does not occur.

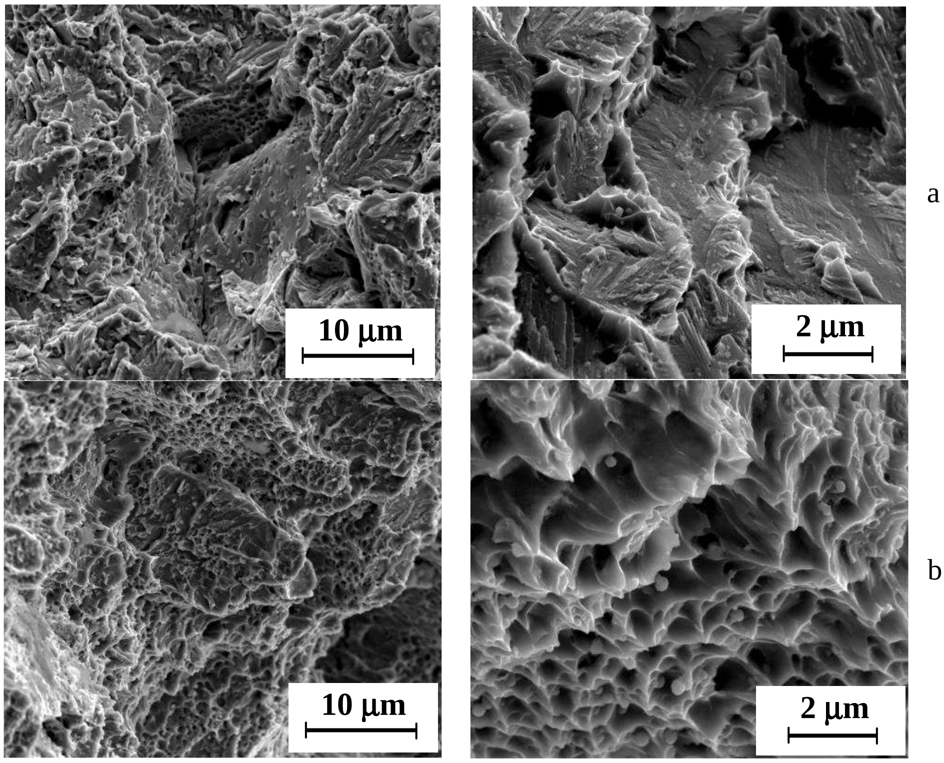


Fig. 7. Morphology of maraging plate fractures after firing with 12,7 AP B-32 type projectile: a – plate no. 3 stopped the projectile, b – plate no. 9 did not stop the projectile

5. CONCLUSIONS

The research conducted implies the following conclusions:

1. The developed technology of vacuum steel melting and its further processing facilitates obtaining of super-clean, ultrahigh-strength, new generation grades of maraging steel with various content of alloying elements such as Fe, Ni, Co, Mo, W and V.
2. The developed technology enables manufacturing of plates with dimensions of 50 × 50 × 10 mm from maraging steel with a high hardness up to 64 HRC (780 HV10).
3. Firing at maraging steel plates with 12,7 mm B-32 type armour piercing incendiary (API) projectiles has shown that the plates are characterized by:
   - various dynamic strength
   - various manner of dynamic cracking

- non axially-symmetric damage of plates (despite plates' material isotropy, projectile symmetry and perpendicular direction of firing at the plates).

4. Plates of experimental maraging steels, which connected with the RHA witness plate, stopped the projectile, behaved like brittle material, cracking and breaking into numerous parts scattered in various directions.
5. The smallest depth of penetration of the RHA witness plate (the best protection ability) – 0,5 mm and 0,6 mm was achieved by application of plates of MS550 steel grade of the highest hardness 64 HRC (780 HV) subject to ageing at T = 490°C and t = 30 h. Application of MS500 grade plates, subject to ageing at the same conditions as MS550 grade plates and of identical hardness 64 HRC, resulted in deeper penetration of the witness plate – 0,8 mm and 1,3 mm, respectively.
6. The lowest hardness of the plate in case of which the RHA witness plate was not pierced, was 58 HRC (640 HV), while in case of plate hardness ≤ 49 HRC (~500 HV), the RHA witness plate was pierced.
7. For MS500 steel grade plates, the smallest depth of penetration of the RHA witness plate (0,5 mm and 0,9 mm) was achieved at hardness equal to 61 HRC, while increase in hardness of such plate to 64 HRC resulted in deepening the penetration (0,8 mm and 1,3 mm).
8. Plates of the lowest hardness – 30 HRC and 36 HRC remained intact due to the highest toughness which is a desirable property of material for armours, however these plates did not present a proper protection ability. Plate of a hardness equal to 36 HRC stopped only the projectile's brass coat, while the core perforated the RHA witness plate.
9. Further research and analyses concerning modification of chemical composition, microstructure and properties of new generation maraging steel should be oriented towards improvement of toughness for a hardness level ≥ 60 HRC (~700 HV). It will be possible to achieve this improvement by reduction of the size of particles of intermetallic phases strengthening the steel, at the same time maintaining sufficient volume of the strengthening phases, by reduction of susceptibility to selective intermetallic phases and carbonitrides precipitation at grain boundaries as well as by reduction of austenite grain size before solution treatment and quenching.

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REFERENCES

[1] Gleiter H., Nanostructured materials: basic concepts and microstructure, *Acta Materialia*, 48, 2000 (1), pp. 1-29, 2000.

[2] Garbarz B., Development limits of construction materials on Fe-based, *Works of Institute for Ferrous Metallurgy*, 62, 2010 (1), pp. 14-21, 2010.

[3] Srivathsa B., Ramakrishnan N., Ballistic performance maps for thick metallic armour, *Journal of Materials Processing Technology*, 96, 1999, pp. 81-91, 1999.

[4] Demir T., Ubeyl M., Yildirim R.O., Effect of Hardness on the Ballistic Impact Behavior of High-Strength Steels Against 7.62-mm Armour Piercing Projectiles, *Journal of Materials Engineering and Performance*, 18, 2009 (2), pp. 145-153, 2009.