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Technological Properties and Applications of High-Carbon Nanobainitic Steels

Abstract: Steels belong to the most popular structural materials. Depending on their chemical compositions and applied heat or thermo-mechanical treatment, steels are characterised by various microstructures as well as diverse mechanical and functional properties. Recent years have seen the significant development related to the design of chemical compositions and manufacturing technologies used in the production of nanostructural steels. The article describes the methods used when manufacturing nanostructural steels and presents characteristics of selected i.e. high-strength nanobainitic steels in terms of their microstructure as well as mechanical and functional properties. The second part of the article is concerned with the present and prospective applications of nanobainitic steel products as well as summarises information found in related reference publications regarding the above-named steels.

Keywords: high-carbin nanobainitic steel, nanostructural steel, mechanical properties of steel

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Introduction

Recent years have seen the significant development of steels characterised by high strength (R_m>1500 MPa). The aforesaid trend results from the growing demand for structures exposed to higher stresses, where the use of high-strength steels is profitable both in terms of cost efficiency and operational properties (e.g. frameworks of high-rise buildings, self-propelled cranes and construction equipment). To provide high structural safety within a wide range of operational properties, high-strength steels should be characterised by high impact energy at sub-zero temperatures (within the range of -40°C to -60°C). Other, simultaneously performed, research works are concerned with new steel grades characterised by strength exceeding 2000 MPa or steels having lower strength, yet characterised by unique operational properties such as high abrasive wear resistance or fatigue. An important issue related to production technologies enabling to obtain the high-strength characterised by required operational properties, the minimum use of alloying elements and the lowest possible manufacturing costs.

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Primary parameters characterising structural steels (subjected to various stresses/loads) include tensile strength, yield strenght, total elongation, impact toughness and crack resistance. To achieve the specified requirements numerous research works are carried out concerning the design of high-strength structural steels without compromising required crack resistance at sub-zero temperatures. In addition, the aforesaid steels should be characterised by high weldability and other technological properties including cold formability, in-use stability etc. In recent years, the development of structural steels has been concerned with quenched and tempered grades such as S690Q, S890Q, S960Q, S1100Q and S1300Q as well as with TMCP (thermomechanicaly controlled processed) steels characterised by higher toughness (S355M, S460M S500M, S700M and S1100M). Figure 1 presents the chronological development of structural steel grades presently used in welded structures.

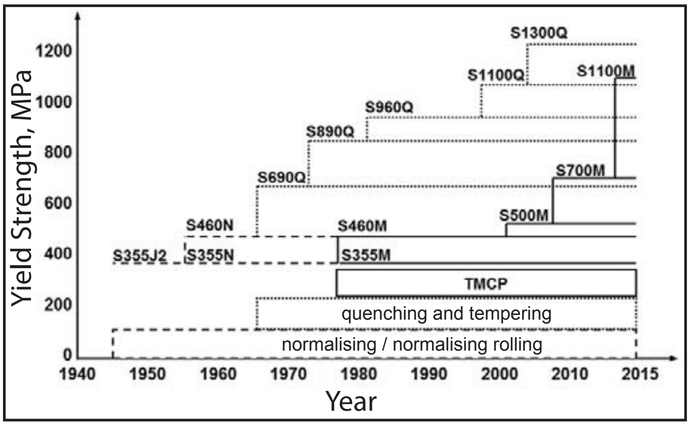

Fig. 1. Development of quenched and tempered structural steels and TMCP steels [1]

The industrially made steels and iron-based alloys characterised by the highest yield strength are maraging type steels (e.g.: X2NiCoMo18-8-5, X2NiCoMo18-9-5, X2NiCoMoTi18-12-4 and X3NiCoMoTi18-9-5), where R_e amounts to up to 2.4 GPa without compromising applicable ductility (A_5=5÷6%). Other research works are concerned with the development of maraging type steel having a yield strength exceeding 3.8 GPa (MS500-550ksi) [2]. Figure 2 presents the maximum yield strength values in relation to the primary groups of structural steel grades made industrially and used when making welded structures or machinery elements. The yield strength and tensile strength are important properties of steels, yet, presently, significant emphasis is given to the development of steels characterised by higher crack resistance, particularly at low temperatures, without compromising the highest possible strength. In addition, it is not less important to develop a production technology enabling to achieve the highest possible strength and ductility with the lowest possible addition of alloying elements, increasing production costs and, usually, worsening the weldability of steels.

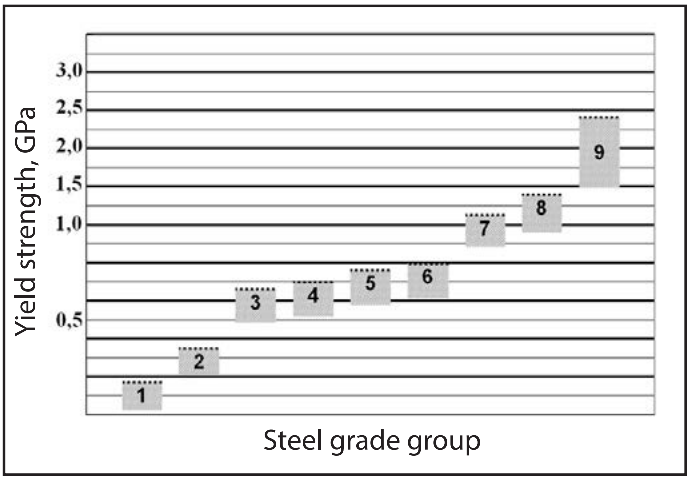

Fig. 2. Maximum yield strength values of structural steel grades presently obtainable in industrial conditions: 1 – IF type steels; 2 – ferritic-pearlitic conventional; 3 – pearlitic-ferritic medium-carbon microalloyed; 4 – low-carbon microalloyed/low-alloy having the ferritic/bainitic structure; 5 – low-alloy multi-phase (ferrite/bainite/martensite); 6 – pearlitic microalloyed/low-alloy; 7 – low-carbon low-alloy/medium-alloy having the microstructure of lath (dislocation) martensite; 8 – alloyed quenched and tempered; 9 – classical maraging [3]

It can be assumed that the maximum strength obtainable in relation to iron and its alloys is the strength of the Fe-α whiskers amounting to approximately 13 GPa. It should be emphasized that the size of the cross-section of tested whiskers did not exceed 8 μm, whereas its maximum length amounted to 20 mm [4]. For this reason, the making of a structural material having the structure of the whisker is highly unlikely. In general, it can be stated that the greater the necessary cross-section of a structural element, the more difficult it is to obtain a microstructure characterised by the satisfactory combination of high strength and high ductility. In relation to small cross-sections of metallic products it is possible to obtain a very high yield strength of up to 5.5 GPa (thin steel wire subjected to very high cold strain in the process of drawing) [5]. However, because of the very small cross-section, the usability of the above-named product is very limited.

In Figure 3, numbers 12, 13 and 14 designate new classes of potentially applicable steels characterised by the highest presently obtainable yield strength [3]. Based on results of tests concerning steels and alloys of group 13 and 14 it can be stated that nearing a yield strength of approximately 3.5 GPa is accompanied by a decrease in ductility to a value close to zero. In view of the foregoing it can be concluded that the primary challenge in relation to research on the development of ultrahigh-strength structural steels and iron alloys is the development of methods making it possible to increase the ductility of the above-named steels and alloys. The

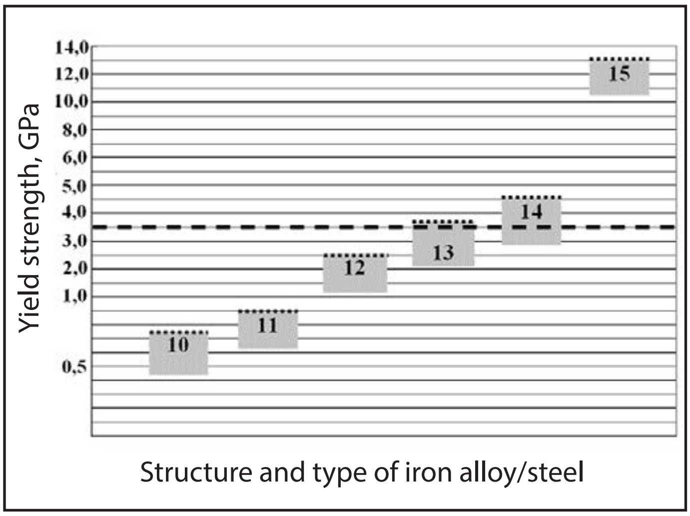

Fig. 3. Maximum presently obtainable yield strength values of steels and iron alloys at the stage of research and development: 10 – unalloyed/low-alloy ferritic/bainitic ultrafine-grained; 11 – unalloyed/low-alloy ferritic/bainitic nanograined; 12 – high-carbon alloy having the nanolath bainite structure; 13 – ultrahigh-strength maraging; 14 – amorphous alloy; 15 – Fe-α whiskers [3]

basis for such research is the development of theories describing deformation and hardening mechanisms. Previously developed theories did not apply to the analysis of deformation processes in relation to nanocrystalline and amorphous structures [3].

Microstructure - nanostructure

One of the methods enabling the effective improvement of mechanical properties of steels is the refinement of the matrix grain, leading to an increase in the yield strength in accordance with the Hall-Petch equation [6] and a decrease in the nil ductility transition temperature (Fig. 4)

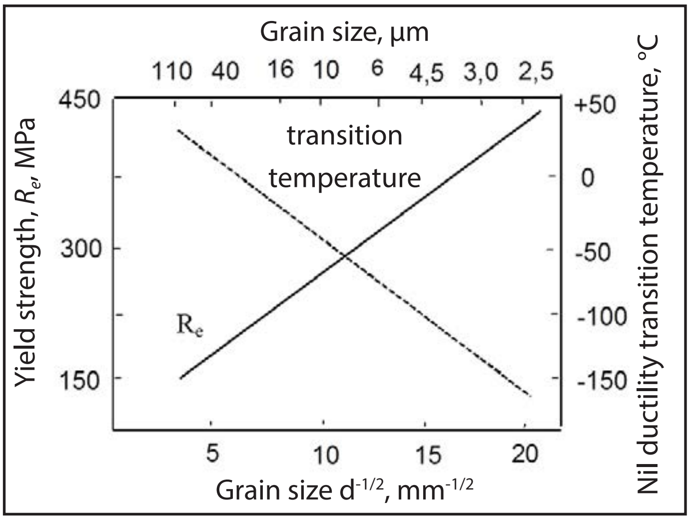

Fig. 4. Effect of the grain size on the yield strength and nil ductility transition temperature [1]

There are 5 classes (types) of the microstructure of metals and single-phase alloys affecting strength, ductility and some other technological and functional properties [7]:

- ideal crystal (monocrystal),
- polycrystalline microstructures:
  - conventional microstructure,
  - ultrafine-grained microstructure,
  - nanograined microstructure,
  - amorphous state (Fig. 5).

In multiphase steels each of the phases can be characterised by one of the above-named refinement degrees. Additional elements of the microstructure are interphase boundaries. By convention, the upper ultimate limit size of the

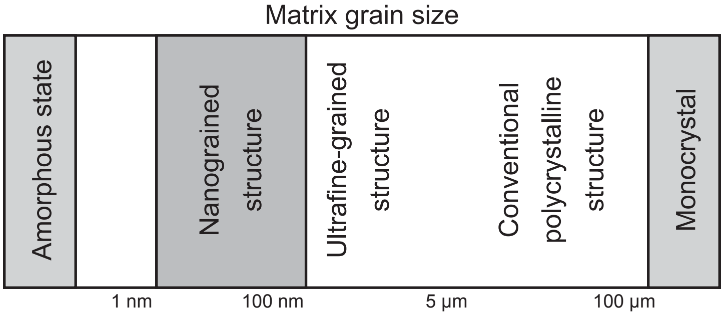

Fig. 5. Structures of metals and alloys in relation to the matrix grain size [7]

matrix grain in relation to a material having the ultrafine-grained microstructure is restricted within the range of 5 μm to 1 μm. Further grain refinement leads to the submicron structure and, afterwards, to the nanocrystalline (nanograined) structure. There are no clear boundaries determining the range of the matrix grain size in relation to the nanostructure. H.K.D.H. Bhadeshia suggested to use the term of "nanostructure" in cases, where the mean size of matrix grains separated by high-angle boundaries, measured using the mean intercept length on the flat cross-section, is restricted within the range of 20 nm to 50 nm [8]. The above definition refers to uniaxial, lamellar and lath microstructures. This study adopted the definition of the nanostructure proposed by Bhadeshia. However, after taking into consideration other proposed definitions, the adopted upper ultimate mean intercept length in relation to the nanograined structure amounted to 100 nm [7].

Nanograined and ultrafine-grained materials can be obtained using the following technologies [9]:

- condensation in inert gas,
- mechanical alloying,
- electrodeposition,
- crystallisation from the amorphous material (devitrification),
- severe plastic deformation,
- methods involving thermomechanical (thermoplastic) processes.

The use of severe plastic deformation enables the formation of the nanostructure in smaller volumes, yet this direction of research did not lead to the development of an industrial technique enabling the manufacturing of large-sized products having the nanometric structure in their entire volume, typical of steel products which could find practical applications. The use of the thermo-mechanical control process when making plates in microalloyed steels enables to achieve a ferrite grain having a minimum size restricted within the range of 2 μm to 3 μm [10]. Further grain refinement could be obtained through high deformation within the ferritic range or even using interoperational cold rolling [11, 12]. The use of complicated deformation operations and heat treatment cycles enable to obtain a grain sized below 1 μm, yet such technologies are unfit for industrial applications [7]. H.K.D.H. Bhadeshia et al. [13–16] demonstrated the possibility of obtaining carbide-free lower bainite having morphological features characteristic of the nanostructure. Although such morphological types of bainite were obtained previously [17], the results of tests performed by H. Bhadeshia paved the way for the development of industrial technologies enabling the manufacturing of nanostructural steel products. In addition to the use of the bainitic transformation when making the nanostructure, research works are also concerned with the obtainment of nanopearlite [18, 19] and nanomartensite [20, 21].

Nanobainitic steel

Microstructure and mechanical properties

A new approach to the making of nanostructures in steels proposed by H. Bhadeshia about 15 years ago [13, 14], involving the controlling of phase transformations, led to the determination of fundamentals applicable when making nanostructural steels having the structure of carbide-free lower bainite and retained austenite, amounting to 15-35% by volume. The necessity of obtaining assumed properties of nanostructural bainitic-austenitic steel (nanobainitic

Table 1. Chemical compositions of nanobainitic steels, wt. % [7, 22-26]

Reference sources	C	Mn	Si	Cr	Mo	V	Ti	Al	Co	Ce**
[7]*	0.55÷ 0.60	2.00÷ 2.15	1.75÷ 1.95	1.25÷ 1.40	0.70÷ 0.85	0.09÷ 0.12	0.006÷ 0.009	0.015÷ 0.025	-	1.40
[22]	0.79	1.98	1.51	0.98	0.24	-	-	1.06	1.58	1.36
[23]	0.79÷ 0.80	1.98÷ 2.01	1.56÷ 1.59	1.0	0.24	-	-	0÷ 1.01	1.51	1.40
[24]	0.87	1.54	1.16	-	0.28	-	-	1.13	-	1.40
[25]	0.82	2.05	1.66	0.22	0.36	-	-	0.051	-	1.22
[26]	0.76	1.04	1.63	1.31	-	0.10	-	0.01	-	1.20

*steel NANOS-BA© developed at Instytut Metalurgii Żelaza (Institute of Ferrous Metallurgy)
** Ce=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15

steel) and taking into consideration the compromise related to the reduction of technological difficulties accompanying the manufacturing process, resulted in the development of grades characterised by various chemical compositions and combinations of strength and ductility (Table 1). Because many applications require high crack resistance, research works are focused on increasing the toughness of products made of nanobainitic steels at high strength.

Nanobainitic steel is characterised by high formability within a temperature range typically applied for hot rolling of structural steels. The final heat treatment of products made of nanobainitic steels can be performed directly after hot rolling or as a separate technological operation. In cases of tests or low-volume production involving the use of various temperatures and processing times, a heat treatment with re-austenitisation is applied. Figure 6 presents the schematic heat treatment of products made of nanobainitic steels. A cooling rate is adjusted in relation to the thickness and the chemical composition of a specific heat so that the one-phase austenitic structure in relation to an isothermal transformation point can be maintained. By adjusting temperature and time of isothermal heat treatment time it is possible (within a certain range) to control mechanical properties of steels [7].

Figure 7 presents a typical structure of the nanobainitic steel observed (using a transmission electron microscope) on a specimen having the form of a thin foil. The microstructure of the steel is composed of lath packets of laths and less regular areas of carbide-free

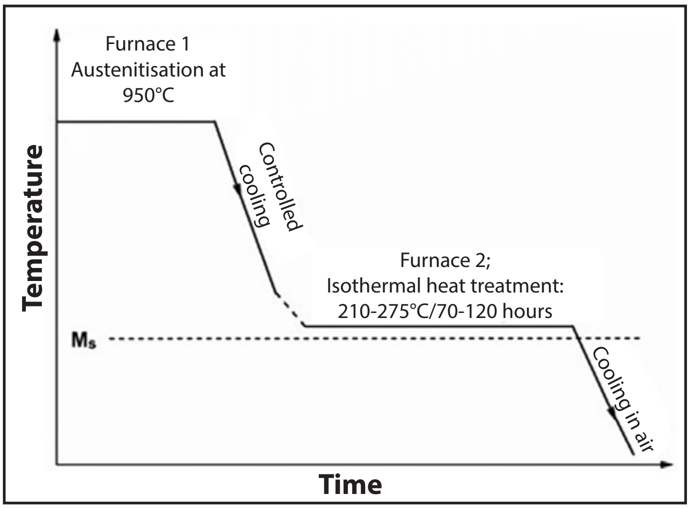

Fig. 6. Schematic final heat treatment of products made of nanobainitic steel [7]

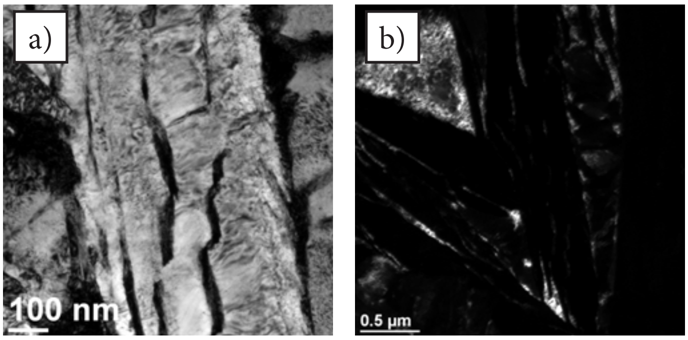

Fig. 7. Microstructure of steel NANOS-BA® subjected to austenitisation at a temperature of 950°C for 20 minutes and to isothermal heat treatment at a temperature of 225°C for 70 hours; thin foil, transmission electron microscope; (a) – example of a typical nanolath structure characterised by high dislocation density, (b) – areas of retained austenite visible in dark field image (bright areas) [7]

bainite characterised by high dislocation density (Fig. 7a) and retained (untransformed) austenite having the form of nanolaths and submicron-sized grains (Fig. 7b). The size of a grain/laths, the arrangement and the volume fraction of morphological constituents depend primarily on the chemical composition, temperature and time of isothermal transformation. As regards steel Nanos-ba©, the mean width of the nanobainite laths was restricted within the range of 60 mm to 100 nm, whereas the content of retained austenite was restricted within the range of 15 to 35% by volume [7].

A characteristic of the nanostructured bainitic-austenitic steel is its high ductility expressed by high values of elongation in tensile static test combined with high strength. The above-named properties result from the structural mechanisms of plastic deformations occurring in the above-named steel, with an important role played by retained austenite. One of the mechanisms increasing ductility is the trip effect, involving the partial or complete strain-induced transformation of retained austenite into "fresh" martensite. Figure 8 presents ranges of tensile strength and total elongation (in a static tensile test), characteristic of various grades of ultrahigh-strength structural steels, i.e. quenched and tempered steels, nanostructured bainitic-austenitic (nanobainitic) steels and maraging steels characterised by the highest strength.

Formability characteristics of ultrahigh-strength steels having various types of the microstructure (Fig. 9) affect the usability of individual steel grades in specific operating conditions. Machinery parts can be repeatedly exposed to strong loads within the elastic range as well as within the range of plastic strains.

Results of tests concerning the mechanical properties of plates made of steel Nanos-ba® subjected to heat treatment (using parameters restricted within the ranges presented in Fig. 6) and of nanobainitic steels subjected to tests in other research centres are presented in Table 2.

As a result of the standard heat treatment performed using the parameters restricted within ranges presented in Figure 6, products made of steel Nanos-ba® are characterised by impact energy restricted within the range of 8 J to 12 J at a temperature of -40°C and by impact energy restricted within the range of 15 J to 20 J at ambient temperature. Known theories concerning mechanisms of crack formation in steels having

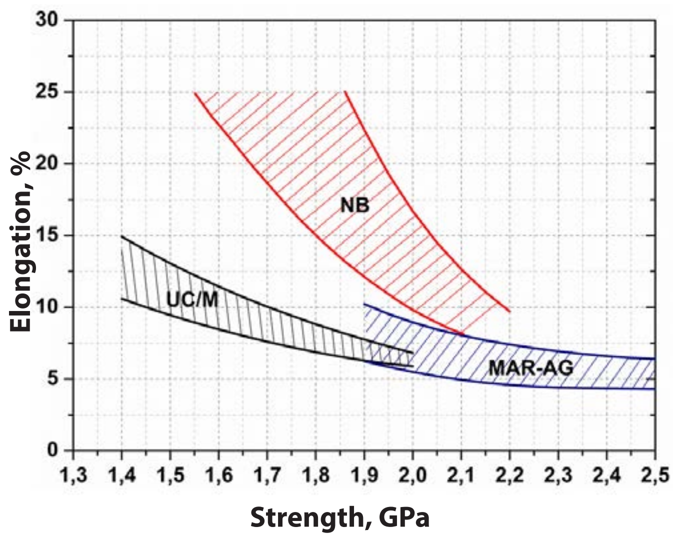

Fig. 8. Ranges of tensile strength and elongation in the tensile test characteristic of various grades of ultra-high-strength structural steels: UC/M – quenched and tempered and martensitic steels, NB – nanobainitic steels, MAR-AG –maraging steels [7]

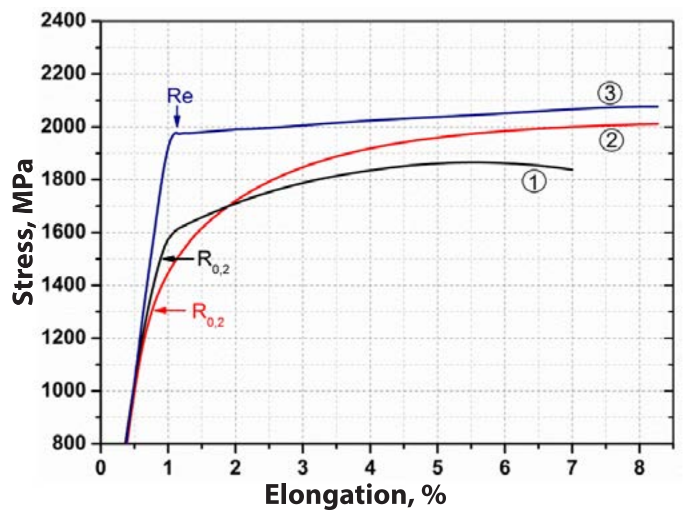

Fig. 9. Schematic tensile curves in the "stress" (calculated as the proportion of force to the initial cross-section) – "percentage total elongation of the specimen" system of ultrahigh-strength steels having various structures: 1 – steel having the martensitic structure or the structure of tempered martensite, 2 – nanobainitic steel, 3 – nanostructured one-phase steel [7]

the lath bainitic structure or martensitic structure revealed that an increase in the toughness of products made of steel NANOS-BA® could be obtained by reducing the size of bainite lath packets [27, 28]. The above-named reduction could be achieved by the refinement or sectioning (division) of primary austenite grain into smaller areas using heat treatment methods, e.g. grain sectioning and isothermal transformation (GSIT) [29]. The aforesaid method enables the refinement of bainite lath packets and, consequently, an increase in toughness. The use of the GSIT-based treatment significantly increased the toughness of nanobainitic steel NANOS-BA® (Fig. 10).

Table 2. Mechanical properties of plates made of steel NANOS-BA® subjected to heat treatment using parameters restricted within the ranges presented in Fig. 6 and of other nanobainitic steel grades [7, 22-25]

Ultimate tensile strength R_m, GPa	Yield strength $R_{0.2}$, GPa	$R_{0.2}/R_m$	Total elongation A_5, %	Uniform elongation A_u, %	Reference publications
1.85÷2.20	1.30÷1.45	0.65÷0.69	12.5÷19.5	9.5÷13.8	[7]**
0.96	0.77	0.80	6.0*	-	[22]
1.70÷2.26	1.24÷1.48	0.62÷0.74	4.6÷29.0*	-	[23]
2.20	-	-	7.06*	-	[24]
1.87	-	-	7.53*	-	[25]

Remarks: *ε_T (total elongation), ** steel NANOS-BA®

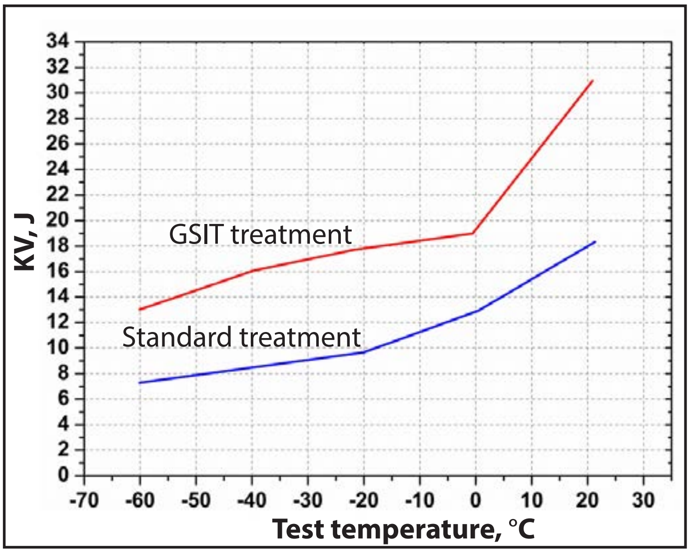

Fig. 10. Impact energy vs. test temperature for the Charpy-V specimens made of steel NANOS-BA® subjected to the standard heat treatment 950oC/225oC/70h and the GSIT treatment: 950°C/160°C/225°C/70 h [29]

Applications and implementation potential of nanobainitic steels

In recent years, applications of nanostructured bainitic steels have been the subject of numerous projects and analysis performed by research centres all over the world. Authors of work [30] presented a wide range of research dedicated to industrial applications of nanostructured steels. The tests involved two groups of steel grades having a carbon content of 0.6% and a carbon content restricted within the range of 1.0% to 0.8%. In the above-named work the authors presented technological stages concerning the manufacturing of products and semi-products made of the nanostructured steels as well as material characteristics within a wide range of mechanical properties, fatigue strength or abrasive wear resistance. The tests related to the making and further processing of materials were performed in industrial conditions, using isothermal temperatures of 220°C, 250°C and 270°C. In relation to steel containing 1% C, the hardness amounted to 625 HV, $R_{0.2}$ was approximately 1.65 GPa; R_m amounted to approximately 2.1 GPa and the total elongation was 16.4%. In relation to steel containing 0.6% C, the hardness amounted to 600 HV, $R_{0.2}$ was approximately 1.5 GPa; R_m amounted to approximately 2.0 GPa and the total elongation was 11.9%. Work [31] involved tests aimed to assess the usability of nanostructured bainitic steel in three chemical composition variants, i.e. Fe-1% C-1.5% Si, Fe-0/.8% C-1.5% Si and Fe-0.6% C-1.5 % Si, in elements of equipment requiring high abrasive wear resistance and fatigue strength. In relation to steel containing 1.0% C in the variant characterised by the fraction of retained austenite volume amounting to 33%, the hardness amounted to 625 HV, $R_{0.2}$ was approximately 1.7 GPa; R_m amounted to approximately 2.1 GPa and the total elongation was 21.3%. In turn, in relation to steel containing 0.6% C in the variant characterised by the fraction of retained austenite volume amounting to 20%, the hardness amounted to 600 HV, $R_{0.2}$ was approximately 1.5 GPa; R_m amounted to approximately 2,0 GPa and the total elongation was 19%. In the abrasive wear resistance tests, the nanostructured steel was characterised by a significantly lower specific wear ratio (SWR), i.e. below 1×10^{-4}, in comparison with standard abrasion resistant steels grades [31]. As regards the fatigue strength of the nanostructured steel, the tests did not reveal any significant advantages over commercial steel grades having the structure of lower bainite or that of tempered martensite. Work [32] presented specific features of the nanostructured steel important in terms of the industrial processing of products, illustrated with an example of the chemical composition Fe-0.55% C-1.95% Mn-1.82% Si-1.29% Cr-0.72% Mo. The authors discussed features of semi-finished products at individual production stages, from casting through plastic working to the final heat treatment. The authors also characterised, among other things, the susceptibility of the nanobainitic steel to interdendritic segregation during solidification and the resultant banding of the microstructure in hot rolled products. In addition, the authors indicated the susceptibility to surface decarburisation and crack formation during cooling, e.g. after hot rolling. It was suggested that the final heat treatment be performed within a continuous process, directly after hot rolling, to prevent the formation of cracks during the cooling of plates to ambient temperature. In relation to the analysed chemical composition of the steel made in industrial conditions in the form of hot rolled sheets/plates having thicknesses restricted within the range of 3 mm to 12 mm, the obtained strength amounted to 1.9-2.0 GPa whereas the total elongation amounted to 15%. The result of the cold bending test to reach an angle of 180° was positive.

The year 2018 saw the completion of the EU project entitled *Understanding basic mechanisms to optimize and predict in-service properties of nanobainitic steels* [33] concerned with the industrial-scale production of nanobainitic steel products for specific applications, e.g. products characterised by high fatigue strength. Project participants indicated advantages and limitations of the production and applications of nanobainitic steels. Special attention was given to unstable mechanical properties manifested by reduced ductility. The participants linked the aforesaid effect with, among other things, the mechanical stability of retained austenite and performed detailed tests to determine the importance of this phase. It should be noted that the test materials were mostly steels characterised by a high carbon content, i.e. min. 0.67%. The obtained strength exceeded 2.0 GPa and the yield strength point reached 1.9 GPa, yet the total elongation not exceeding approximately 12% and, particularly, impact energy (KV) below 10 J were not satisfactory. The report is a valuable material-related database containing results of tests concerning properties and the microstructure of nanobainitic steels. In relation to 0.6% C-1.5% Si steels, the authors demonstrated that the content of carbon in retained austenite in the form of blocks (grains) amounted to 3.2 at.% and 6.2-7.5 at.% in relation to an isothermal transformation at 220°C and 250°C respectively (6 at.% of carbon corresponds to 1.5% wt. %). In turn, the content of carbon in austenite in the form of thin laths (film having a thickness restricted within the range of 5 nm to 15 nm) was restricted within the range of 10 at.% to 17 at.% and did not depend on the isothermal transformation temperature.

Authors of works [34, 35] demonstrated the application potential of nanostructured steels in high-energy impact occuring under conditions, when ballistic shields are exposed to fire. In works [34, 35] the authors presented exemplary applications of bainitic steels in the form

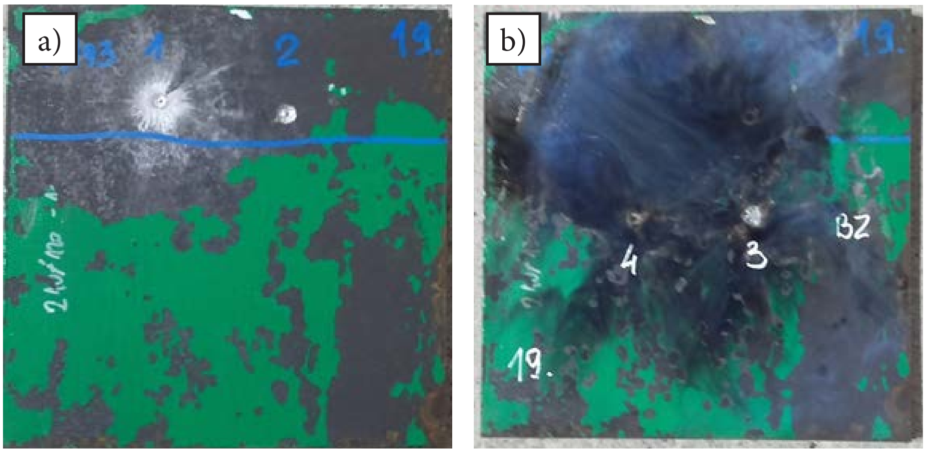

Fig. 11. Photograph of 10 mm thick plate made of nanobainitic steel NANOS-BA-210/120 exposed to armour-piercing fire; positive test results – the lack of penetration and cracks on the plate.
(a) ammunition cal. 5.56x45 mm M193; 1 – 980.5 m/s; 2 – 984.1 m/s
(b) ammunition cal. 7.62x39 mm API BZ; 3 – 722.6 m/s; 4 – 731.4 m/s

Table 3. Prospective applications of nanobainitic steels

Industrial sector	Applications
Defence industry	Armour elements
Machinery industry	Cutting tools, bearings
Mining and mineral industry	Parts of equipment characterised by high abrasive wear resistance
Automotive industry	Elements of injection systems in Diesel engines
Aerospace industry	Element of aircraft landing gear
Others	Frames of mountain bikes

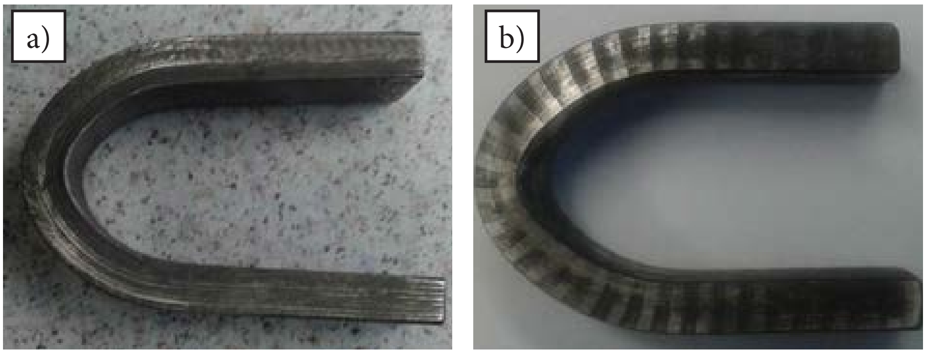

Fig. 12. Specimens of steel NANOS-BA© after the bend test
(a: variant 210/120; b: variant 275/120)

of armour shields. The plates were exposed to armour-piercing ammunition fire, in accordance with the Stanag 4569 requirements [36] in relation to level 1 and 2 (Fig. 11) .

High mechanical properties combined with satisfactory toughness [37] are decisive for practical applications of new steel grades, e.g. in structures and/or machinery elements (Table 3). Other important factors include technological properties adjusted to existing or planned manufacturing processes and acceptable production costs.

The production technology of nanobainitic steels requires extended low temperature heat treatment lasting between 70 and as many as 400 hours (depending on the chemical composition and required properties). In addition, a high carbon content restricted within the range of approximately 0.5% to approximately 1.0% is the reason for technological problems including susceptibility to cracking resulting from the exceeding of a specific cooling rate. Presently, many laboratories are carrying out research aimed to optimise the technology and reduce nanobainitic steel production costs (particularly process duration). The machining, including cutting and grinding, of products made of nanobainitic steels should be applied so that a heating temperature should not exceed a isothermal processing temperature. Bending or forming following the finishing heat treatment is possible, yet plastic deformation accompanying the above-named operations induce structural changes (primarily the transformation of retained austenite into "fresh" martensite) and, consequently, significant changes in mechanical properties. The effect of plastic deformation on the mechanical properties of products made of nanobainitic steels are not sufficiently known yet. Where possible, the forming operation should be performed before the final heat treatment, in the softened state, after slowed down cooling from the austenite stability range or after soft annealing at temperature below A_1.

Figure 12 presents photographs of the specimens after static bend tests. The static bend tests of nanobainitic steel Nanos-ba© were performed using specimens cut out of 8 mm thick plates using a a bending bar of a diameter 35 mm and the distance between the supports amounting to approximately 80 mm. The adopted bending conditions were the same as in relation to plates of standard martensitic armour steels. The tests involved selected types of heat treatment. Specimens 210/120 and 275/120 were subjected to bending to reach an angle of 180° after unloading. During the tests the obtained angle exceeded 180°. The surfaces of the bent specimens did not reveal cracks nor were they partially torn in the bent areas; the images of the areas subjected to observations were magnified several times.

Weldability of nanobainitic steels

The nanobainitic steel is characterised by a carbon equivalent (Ce) restricted within the range of 1.2 to 1.4 (Table 1), leading to limited weldability [7]. In turn, a high carbon content restricted within the range of 0.55% to 1.0% increases the susceptibility of the steel to hardening as well as to crack formation in the weld and in the HAZ. At the same time, a high carbon content of up to 1% makes it possible to reduce the temperature of the martensitic transformation, in order to form the nanobainite. A similar effect can be obtained using a high content of nickel combined with a reduced content of carbon. However, previously developed theories indicate that the level of a substitutive chemical element necessary for the reduction of the martensitic transformation temperature could preclude the formation of bainite because an excessive content of nickel reduces the difference between temperature B_s and M_s [39]. In cases of low carbon contents it was noticed [40] that thin laths of bainite tended to merge and formed grains of larger sizes, thus reducing strength and impact energy [41, 42]. Until today, the research works dedicated to the development of nanobainitic steels characterised by low carbon contents have not produced desirable results.

Nanobainitic steels are also characterised by a high content of manganese (1.0÷2.15%), which combined with a carbon content of more than 0.5% results in deteriorated weldability. A silicon content in nanobainitic steels restricted within the range of 1.16% to 1.95% may lead to the lamellar cracking of plates, induced by welding process-related heating and shrinking. A chromium content of up to 1.4% is responsible for the significant hardening of the heat affected zone, necessitating the application of preheating. Another chemical element worsening the weldability of nanobainitic steels is molybdenum (up to 0.85%), increasing the hardenability of the HAZ [43].

Taking into consideration the chemical composition leads to the conclusion that the welding of nanobainitic steels could be accompanied by the following problems [44]:

- cold cracking,
- formation of brittle martensite,
- precipitation of cementite.

The prevention of the above-named negative phenomena accompanying the welding of nanobainitic steels may require the use of preheating and a precisely adjusted heat input to the joint. On the other hand, nanobainitic steels are characterised by the significant heat treatment-induced grain refinement. During welding, the temperature in the HAZ exceeds the temperature accompanying the heat treatment process. The foregoing leads to irreversible microstructural changes in the heat affected zone. One of solutions could involve the welding of elements in the state preceding the heat treatment (i.e. in the softened state) and subjecting the obtained joints to the final heat treatment. Other solutions could involve the process of welding performed with the use of a filler metal or the performance of the post-weld heat treatment of the joints.

Previously performed MMA welding tests involved the nanobainitic steel characterised by a strength of 2500 MPa. The objective of work [45] was to investigate the effect of a high silicon content (restricted within the range of 0.86% to 1.63%) in the weld deposit on the properties of joints and the microstructure. Static tensile tests revealed that the yield strength of the weld deposit was lower than 830 MPa, whereas its tensile strength amounted to 950 MPa. The weld deposit microstructure was composed of bainite and martensite. The microstructure did not contain ferrite formed as a result of the diffusive transformation (known as allotriomorphic ferrite) [46] nor did it contain the Widmanstätten type structure, present in weld deposits of typical structural steels.

L. Yuan et al. [47] subjected a structural steel to laser surfacing performed using a nanobainitic filler metal characterised by a strength of 1280 MPa and an elongation of 6.4%. Subsequent metallographic tests revealed that the overlay weld microstructure was composed of nanobainite and retained austenite. The width of bainite laths was restricted within the range of 50 nm to 80 nm, whereas the width of austenite laths was restricted within the range of 10 nm to 30 nm. The mean hardness of the overlay weld amounted to 610 HV.

S.G. Hong et al. [48] made laser welded joints in a nanobainitic steel (Fe-0.78% C-1.03% Si-1.54%Mn). The authors suggested that the welding process be followed by an additional heat treatment aimed to eliminate cold cracking and prevent the formation of the undesirable martensitic microstructure. The additional heat treatment involved the reduction of the joint temperature to T_L ($<M_s$) followed by fast heating (in less than 10 seconds) to temperature T_u ($>A_{c1}$) and by cooling to room temperature. The applied heat treatment resulted in the formation of the ferritic microstructure with a slight amount of retained austenite and cementite in the HAZ. The hardness in the HAZ amounted to 350 HV. The joints did not reveal the presence of cold cracks. The authors did not present results of tests concerning the mechanical properties of the joints.

K. Fang et al. [24] develop a TIG welding-based method enabling the joining of a nanobainitic steel (0.87% C, 1.16% Si, 1.54% Mn, 0.49% Ni, 113% Al). The above-named method involved an additional mechanical treatment performed directly after the welding process. The aforesaid method involved the movement of the impact head travelling at a constant rate (welding rate amounted to 1.5 mm/s). The head followed the welding torch at a distance of 30 mm. The temperature of the area subjected to impact amounted to 600°C and was monitored during the process. After the completion of the welding process, the joints were subjected to a heat treatment in a furnace. The heat treatment was performed at a temperature of 250°C and was 1.5 and 2.5 hours in duration. The use of the additional impact and heat treatment led to an increase in the content of bainite (from 40% to 80%) in the steel and prevented the formation of cracks. Additional technological procedures enabled the refinement of bainite laths.

The use of additional heat treatment makes it possible to increase the strength of a joint. The authors of work [25] made a TIG welded joint in a nanobainitic steel (0.82% C, 1.66% Si, 2.05% Mn, 0.36% Mo, 1.06% Ni, 0.05% Al) and subjected the joint to a 5 day-long heat treatment at a temperature of 230°C and 250°C. The strength of the base material in the as-delivered state amounted to 1877 MPa, whereas the elongation amounted to 7.53%. After the heat treatment at a temperature of 250°C, the strength of the joint amounted to 1913 MPa, whereas the elongation amounted to 5.14%. In turn, after the heat treatment at a temperature of 230°C, R_m=2115 MPa, whereas A=2.3%. The use of additional heat treatment reduced the hardness in the welded joint to 600 HV. Before the heat treatment, the above-named hardness amounted to more than 850 HV [26].

The study of available reference publications concerning the welding of nanobainitic steels justifies the conclusion that the above-named issue is not well known yet. For this reason, having in view the prospective applications of nanobainitic steels it is necessary to test their weldability. It can be hypothetically assumed that the most favourable joining methods in terms of nanobainitic steels should be arc methods, e.g. TIG, and friction welding in the solid state. Both methods enable the making of welded joints without the use of filler metals and allow the precise adjustment of technological parameters of the process. The next article by the authors of this study will present test results concerning welded joints made of nanobainitic steels. Further research will involve tests performed using the MIG/MAG method and concentrated welding power sources.

Summary

Increasingly high requirements related to strength of the structures combined with reduced weight necessitate the development of new structural materials, including innovative grades of steels. Recent years have seen significant progress in the development of chemical compositions and technologies enabling the manufacturing of nanostructured (including nanobainitic) steels. Nanobainitic steels are characterised by high strength (R_m up to 2200 MPa) and satisfactory toughness. As a result, nanobainitic steels can be used when making structures and machinery elements. Various research works have revealed the significant application potential of nanobainitic steels high-energy impact conditions, e.g. as ballistic shields. It should be noted that among structural materials used in mass applications, nanobainitic steels are characterised by the highest strength-ductility product (R_mxA). The strength of nanobainitic steels is similar to that of maraging steels, yet the latter are significantly more expensive.

The production of elements made of nanobainitic steels is significantly inconvenienced by a long final heat treatment and a high carbon content (up to 1%), leading to technological problems and limited technological and metallurgical weldability. The first issue is being approached by performing intense research works aimed to modify the chemical composition of bainitic steels enabling the reduction of heat treatment duration. The second problem requires the use of preheating and/or post-weld heat treatment.

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References:

[1] Brózda J., Jachym R., Kwieciński K., Łomozik M., Węglowski M.St.: *Stale konstrukcyjne i ich spawalność*. Script –training materials, Instytut Spawalnictwa, Gliwice 2017.

[2] Garbarz B., Marcisz J., Burian W.: *Ultrawysokowytrzymałe stale o strukturze nanokrystalicznej*. NANOTECHNOLOGIA-PL, 2010, conference materials. http://science24.com/paper/23291

[3] Garbarz B.: *Granice rozwoju materiałów konstrukcyjnych na bazie żelaza*. Prace Instytutu Metalurgii Żelaza, 2010, vol. 62, no. 1, pp. 14-21.

[4] Brenner S.S.: *The growth of whiskers by the reduction of metal salts.* Acta Metallurgica, vol. 4, 1956, pp. 62-74. https://doi.org/10.1016/0001-6160(56)90111-0

[5] Bhadeshia H.K.D.H., Harada H.: *High strength (5GPa) steel wire: an atom –probe study.* Applied Surface Science, 1993, vol. 67, no. 1-4, 328-333. http://dx.doi.org/10.1016/0169-4332(93)90334-8

[6] Takaki S.: *Review on the Hall-Petch Relation in Ferritic Steel.* Materials Science Forum, 2010, vol. 654-656, 11-16. http://dx.doi.org/10.4028/www.scientific.net/msf.654-656.11

[7] Garbarz B.: *Perspektywy rozwoju technologii wytwarzania i zastosowań wyrobów z ultrawytrzymałych stali nanobaintycznych.* Prace Instytutu Metalurgii Żelaza, 2015, vol. 67, no. 2, pp. 65-79.
[8] Bhadhesia H.K.D.H.: *Nanostructured bainite.* Proceedings of the Royal Society A, 2010, vol. 466, pp. 3-18. https://doi.org/10.1098/rspa.2009.0407
[9] Burian W., Garbarz B.: *Metody otrzymywania nanostruktur w metalach i stopach oraz mechanizmy odkształcenia plastycznego stopów nanostrukturalnych.* Prace Instytutu Metalurgii Żelaza, vol. 61, no. 1, 2009, pp. 1-8.
[10] Howe A.: *Industry prospective on ultrafine grained steels.* Materials Science and Technology, 2009, t. 25, no. 7, pp. 815-819. https://doi.org/10.1179/174328409X441247
[11] Qiu H., Ohmori A., Hagiwara Y.: *Mechanical Properties of Welded Joints of 780 MPa Grade Ultra-fine Grained Steels.* The Iron and Steel Institute of Japan International, 2003, vol. 43, no. 12, pp. 2046-2053. https://doi.org/10.2355/isijinternational.43.2046
[12] Priestner R., Ibraheem A. K.: *Processing of steel for ultrafine ferrite grain structures.* Materials Science and Technology, 2000, vol. 16, pp. 1267- 1272. https://doi.org/10.1179/026708300101507497
[13] Caballero F. G., Bhadeshia H. K. D. H., Mawella K. J. A., Jones D. G., Brown P.: *Very strong low temperature bainite.* Materials Science and Technology, 2002, vol. 18, pp. 279-284. https://doi.org/10.1179/026708301225000725
[14] Garcia-Mateo C., Caballero F. G., Bhadeshia H. K. D. H.: *Development of Hard Bainite.* The Iron and Steel Institute of Japan International, 2003, vol. 43, no. 8, pp. 1238-1243. https://doi.org/10.2355/isijinternational.43.1238
[15] Garcia-Mateo C., Caballero F. G., Bhadeshia H. K. D. H.: *Acceleration of Low-temperature Bainite.* The Iron and Steel Institute of Japan International, 2003, vol. 43, no. 11, pp. 1821-1825. https://doi.org/10.2355/isijinternational.43.1821
[16] Caballero F.G., Bhadeshia H.K.D.H.: *Very strong bainite.* Current Opinion in Solid State and Materials Science, 2004, tom 8, no. 3-4, pp. 251-257. https://doi.org/10.1016/j.cossms.2004.09.005
[17] Wenyan L., Jingxin Q., Hesheng S.: *Fatigue crack growth behaviour of a Si-Mn steel with carbide-free lathy bainite.* Journal of Materials Science, 1997, vol. 32, no. 2, pp. 427-430. https://doi.org/10.1023/A:1018565702991
[18] Wu K.M., Bhadeshia H.K.D.H.: *Extremely Fine Pearlite by Continuous Cooling Transformation.* Scripta Materialia, 2012, vol. 67, 2012, pp. 53-56. https://doi.org/10.1016/j.scriptamat.2012.03.019
[19] Bakshi S.D., Leiro A., Prakash B., Bhadeshia H.K.D.H.: *Dry rolling/sliding wear of nanostructured pearlite.* Materials Science Technology, 2015, vol. 31, no. 14, pp. 1735-1744. https://doi.org/10.1179/1743284714Y.0000000751
[20] Wang X.D., Zhong N., Rong Y.H., Hsu T.Y.: *Novel ultrahigh-strength nanolath martensitic steel by quenching-partitioning-tempering process.* Journal of Materials Research, 2009, vol. 24, no. 1, pp. 260-267. https://doi.org/10.1557/JMR.2009.0029
[21] Hu F., Wu K.M., Misra R.D.K.: *Nanostructured martensiteaustenite dual phase steels.* Materials Science Technology, 2012, vol. 28, pp. 1314-1319. https://doi.org/10.1179/1743284712Y.0000000068
[22] Timokhina I.B., Beladi H. et al.: *Nanoscale microstructural characterization of a nanobainitic steel.* Acta Materialia, 2011, vol. 59, pp. 5511–5522. https://doi.org/10.1016/j.actamat.2011.05.024
[23] Mateo C.G., Caballero F. G.: *The Role of Retained Austenite on Tensile Properties of Steels with Bainitic Microstructures.* Materials Transactions, 2005, vol. 46,

no. 8, pp. 1839-1846.
https://doi.org/10.2320/matertrans.46.1839

[24] Fang K., Yang J.G. i inni.: *Acceleration of regeneration treatment for nanostructured bainitic steel by rotary impacting trailed welding.* Journal of Materials Processing Technology, 2014, vol. 214, 2935–2940.
https://doi.org/10.1016/j.jmatprotec.2014.06.024

[25] Fang K., Yang J.G. et al.: *Microstructure and Mechanical Properties of Nanostructured Bainite Weld with Regeneration.* Metals and Materials International, 2014, vol. 20, no. 5, 2014, pp. 923-928.
https://doi.org/10.1007/s12540-014-5018-6

[26] Fang K., Yang J.G. et al.: *Regeneration Technique for Welding Nanostructured Bainite.* Materials and Design, 2013, vol. 50, pp. 38-43.
https://doi.org/10.1016/j.matdes.2013.02.019

[27] Garbarz B., Niżnik B., Zalecki W.: *Opracowanie podstaw technologii obróbki cieplnej ultrawytrzymałej stali konstrukcyjnej w celu wytworzenia trójfazowej struktury nanokompozytowej o zwiększonej odporności na pękanie w stosunku do poziomu osiąganego obecnie.* Sprawozdanie IMŻ no. So 0835, 2013.

[28] Garbarz B., Niżnik-Harańczyk B.: *Modification of microstructure to increase impact toughness of nanostructured bainite–austenite steel.* Materials Science and Technology, 2015, vol. 31, no. 7, pp. 773-780.
https://doi.org/10.1179/1743284714Y.0000000675

[29] Garbarz B., Niżnik-Harańczyk B.: *Eksperymentalna weryfikacja możliwości zastosowania nanostrukturalnej stali bainityczna-austenitycznej do wytwarzania odkuwek matrycowych.* Prace IMŻ, 2015, vol. 67, no. 1, pp. 1-9.

[30] Garcia-Mateo C., Sourmail T. et al.: *Nanostructured steel industrialisation: plausible reality.* Materials Science and Technology, 2014, vol. 30, no. 9, pp. 1071-1078.
https://doi.org/10.1179/1743284713Y.0000000428

[31] Sourmail T., Caballero F.G., Garcia-Mateo C. et al.: *Evaluation of potential of high Si high C steel nanostructured bainite for wear and fatigue applications.* Materials Science and Technology, 2013, vol. 29, no. 10, pp. 1166-1173.
https://doi.org/10.1179/1743284713Y.0000000242

[32] Garbarz B., Marcisz J., Burian W.: *Technological peculiarities of manufacturing nanobainitic steel plates.* Metec, 2015, Düsseldorf, 15 – 19, June 2015.

[33] *Understanding basic mechanism to optimize and predict in service properties of nanobainitic steels (Mecbain).* Final report. Research Fund for Coal and Steel.

[34] Burian W., Marcisz J., Garbarz B., Starczewski L.: *Nanostructured bainite-austenite steel for armours construction.* Archives of Metallurgy and Materials, 2014, vol. 59, no. 3, pp. 1211-1216.
https://doi.org/10.2478/amm-2014-0210

[35] Marcisz J., Burian W., Stępień J. et al.: *Static, dynamic and ballistic properties of bainite-austenite steel for armours.* 28th International Symposium on Ballistics, 2014, Atlanta, Usa, pp. 1348 – 1361.

[36] Stanag 4569 „*Procedures for evaluating the protection levels of logistic and light armoured vehicles for KE and artillery threat*".

[37] Mason D., Ozberk E. et al.: *Corrosion resistance of nanobainitic steel.* Australasian Corrosion Association (aca) Conference, Adelaide, Australia, 2010.

[38] https://www.nanowerk.com/spotlight/spotid=16203.php

[39] Bhadeshia, H. K. D. H.: *Hard bainite.* Solid–solid phase transformations, 2005, vol. 1, pp. 469–484.

[40] Yang, H.S., Bhadeshia H.K.D.H.: *Designing low-carbon, low-temperature bainite.* Materials Science Technology, 2008, vol. 24, pp. 335–342.
https://doi.org/10.1179/174328408X275982

[41] Keehan, E., Karlsson, L., Andrén, H.O.: *Influence of C, Mn and Ni on strong steel weld metals: part 1, effect of nickel.* Science Technology Welding and Joining, 2006, vol. 11, pp. 1–8. https://doi.org/10.1179/174329306X77830

[42] Pak J. H., Bhadeshia H.K.D.H., Karlsson L., Keehan E.: *Coalesced bainite by isothermal transformation of reheated weld metal.* Science Technology Welding and Joining. 2008, vol. 13, pp. 593–597. https://doi.org/10.1179/ 136217108X338926

[43] Tasak E.: *Spawalność stali.* Fotobit, Kraków, 2002.

[44] Fang K, Yang J et al.: *Review of Nanobainite Steel Welding.* Advanced Materials Research, 2012, vol. 482-484, pp. 2405-2408. https://doi.org/10.4028/www.scientific.net/AMR.482-484.2405

[45] Bhadeshia H.K.D.H., Lord M., Svensson L.E.: *Silicon–Rich Bainitic Steel Welds.* Proceedings of International Conference: Joining & Welding Solutions to Industrial Problems, JWRI, Osaka University, 2003, pp. 43-52.

[46] Ranatowski E.: *Użyteczność obliczeniowej mechaniki spawania w procesie kształtowania technologii.* Advances in Materials Science, 2008, vol. 8, no. 2, pp. 61-68. https://doi.org/10.2478/v10077-008-0032-3

[47] Yuan L., Li Z.G., Huang J.: *Microstructure and Properties of Laser Cladded Nanostructured Bainite Coatings.* China Surface Engineering, 2011, vol. 24, no. 1, pp. 40-44.

[48] Hong S.G.: *Effects of post weld rapid heat treatment on microstructural evolution in high-carbon bainitic steel weld.* In: 63rd Annual Assembly & International Conference of the International Institute of Welding, Istanbul, Turkey, 11-17 July, 2010.