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# Characteristics of Fusion Welded and Friction Welded Joints Made in High-Carbon Nanobainitic Steels

**Abstract:** Intense research on the metallurgy of iron alloys have recently resulted in the development of technologies enabling the making of high-carbon nanobainitic steels. Because of their chemical composition, the above-named steels belong to hard-to-weld materials. To identify the possibility of welding such steels using arc-based methods and welding in the solid state it was necessary to make test joints and perform related metallographic tests. The test results revealed that it is possible to obtain both fusion and pressure welded joints if the process was performed in the softened state, i.e. before the final heat treatment. Afterwards, joints should be subjected to a heat treatment ensuring the obtainment of a previously assumed microstructure and required hardness distribution in the weld and HAZ.

**Keywords:** nanobainitic steels, TIG welding, friction welding, microstructure

**DOI:** *10.17729/ebis.2018.4/1*

## Introduction

The development of modern structural materials satisfying high quality-related, functional and strength-related requirements results from the need for designing and manufacturing structural steels and special vehicles used both in military and civilian applications. Until today, commonly used steels include toughened (hardened and tempered) steels having a yield point of up to 1300 MPa [1], TMCP steels having a yield point of up to 1100 MPa and steels used in ballistic shields, characterised by hardness below 550 HB [2]. These three groups of structural materials are characterised by high mechanical properties and weldability (if made in a manner satisfying related technological recommendations) [2, 3]. As the above-named steels have been used and known for many years, their properties are beginning to fail to meet demands of design engineers, e.g. in terms of strength. Users of steel products expect a further increase in their strength ($R_m$) without

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compromising ductility (impact energy) and special functional properties (abrasive wear resistance, resistance to high-energy impact). In 2018, the global market of high-strength steels (used in automotive, extractive, aviation, ship-building, military and civil engineering industries) will be worth approximately 18.7 billion USD to have reached massive 29.9 billion USD by 2023 [4]. The above-presented information indicates the growing importance and popularity of high-strength steels, yet industrial sectors using such steels continue to search for new iron alloy-based materials.

It should be noted that presently available manufacturing technologies limit the possibility of making steels characterised by even higher mechanical, plastic and functional properties. New market demands can be addressed by nano-steels characterised by highly refined grains, e.g. nanobainitic steels. Publication [5] presents the characteristics concerning the making of nanobainitic steels, their properties and possible areas of application. The extension of possible applicability of nanobainitic steels requires the development of technologies enabling the joining of such steels without compromising their mechanical properties. Undoubtedly, a restriction which must be taken into consideration when welding nanobainitic steels is high a carbon content restricted within the range of 0.55% to 1.0% as well as high contents of other chemical elements are responsible the carbon equivalent in such steels being restricted within the range of 1.2% to 1.4%. The present-day knowledge related to the weldability of structural steels concerns nanobainitic steels to a very limited extent. It is assumed that steels having a carbon content of more than 0.6% are unweldable, whereas those characterised by a carbon equivalent of more than 0.45% are characterised by higher susceptibility to cold cracking.

The analysis of reference publications concerning the welding of nanobainitic steels led to the conclusion that the issue is not very well known [6-9]. To identify the applicability of bainitic steels it was necessary to perform welding tests concerning the above-named steels and determine the effect of a welding thermal cycle on changes in the microstructure and hardness in the welded joint.

H.K.D.H. Bhadeshia et al. [6] demonstrated that the microstructure of the weld deposit of nanobainitic steel was composed of bainite and martensite. Related metallographic tests did not reveal ferrite formed as a result of a diffusive transformation and the Widmanstätten type structure. L. Yuan et al. [7] performed metallographic tests of overlay welds made of nanobainitic steels and revealed that the microstructure was composed of nanobainite and retained austenite. The width of the bainite laths amounted to 50-80 nm, whereas the width of retained austenite amounted to 10-30 nm. The average hardness of an overlay weld amounted to 610 HV. To control phase transformations in a joint, S.G. Hong et al. [8] performed additional heat treatment leading to the obtainment of the HAZ characterised by the ferritic microstructure with a slight amount of retained austenite and cementite having hardness below 350 HV. Additional impact treatment accompanying the welding process made it possible to control the microstructure of the welded joint. As a result of impact and heat treatment, Fang et al. [9] increased the amount of bainite (from 40% to 80%) and refined bainite laths in the weld of a TIG-welded joint.

The study aimed to determine the effect of selected processes involving the fusion welding or pressure welding of nanobainitic steels on the microstructure and the distribution of hardness in the joint area. The tests were performed using the TIG method and the conventional rotational friction welding process. The tests involved experimental high-carbon nanobainitic steels developed and made at Institute for Ferrous Metallurgy (Instytut Metalurgii Żelaza) in Gliwice.

Table 1. Chemical composition of the experimental test steels and commercial high-strength steels

| No. | Steel designation | Contents of chemical elements, % by weight | | | | | | | | | | | ppm | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | Si | P | S | Al | Cr | Mo | V | Ni | $C_e$ | N | O |
| 1 | BAL | 0,61 | 1,53 | 1,67 | 0,007 | 0,007 | 0,015 | 1,30 | - | | - | 1,15 | 36 | 8 |
| 2 | BA | 0,55 | 1,95 | 1,82 | 0,011 | 0,004 | 0,023 | 1,29 | 0,72 | 0,10 | - | 1,30 | 30 | 18 |
| 3 | Strength (Weldox) 1300 | 0,21 | 0,85 | 0,21 | 0,008 | 0,002 | 0,005 | 0,47 | 0,39 | 0,021 | - | 0,61 | 38 | - |
| 4 | ARMSTAL 550 | 0,40 | 1,20 | 0,40 | - | - | - | 1,00 | 0,70 | - | 2,50 | 1,10 | - | - |

## Experimental methodology

The research-related activities included the performance of technological welding tests involving the conventional rotational friction welding and TIG welding. The welding tests were performed using a ZT-4-13 friction welding machine and the following welding parameters:

– $P_t$=2.5 atm. – friction pressure,
– $P_s$=4.5 atm. – upsetting pressure,
– $t_t$=12 s – friction time,
– $t_s$=4.5 s – upsetting time,
– rate of rotation amounted to 1600 rpm.

A bar having a diameter of 20 mm, made of steel C45 was welded with 8 mm and 13 mm thick test plates made of steel BA and BAL.

TIG-welded joints were made using the following technological parameters:

– welding rate of 10 cm/min,
– welding current (impulse) of 160 A,
– welding current (base) of 100 A,
– impulse frequency of 30 Hz,
– shielding gas (100% Ar) flow ware of 15 l/min.

The welding process was performed without the use of a filler metal. The joints were subjected to square butt weld preparation. Plates (5 mm and 8 mm thick) subjected to welding were made of steel grades BA and BAL. The welding process was preceded by preheating up to a temperature of 230°C.

Metallographic tests were performed using an Eclipse MA 200 light microscope (NIKON) and an Inspect F scanning electron microscope. Vickers hardness tests were performed using a KB50 FA automatic testing machine (Prüftechnik GmbH) and a Swiss Max 300 tester.

Table 2. Mechanical properties of the experimental test steels and the steels used for comparative purposes (material condition: after the final heat treatment). Properties of the nanobainitic steels were determined using 5.0 mm thick flat specimens

| No. | Steel designation* | $R_m$ [MPa] | $R_{p0,2}$ [MPa] | $A_5$ [%] | Hardness |
|---|---|---|---|---|---|
| 1 | BAL13 (225/20) | 2195 | 1270 | 11,7 | 610 HV |
| 2 | BAL8 (225/20) | | | | |
| 3 | BA5 (210/120) | 2080 | 1340 | 12,0 | 640 HV |
| 4 | BA6 (250/70) | 1650 | 1200 | 15,0 | 530 HV |
| 5 | BA8 (210/120) | 2050 | 1300 | 12,0 | 630 HV |
| 6 | Strength (Weldox) 1300 | 1572 | 1356 | 10,8 | 501 HV |
| 7 | ARMSTAL 550 | 1600 | 1800 | 7,0 | 570 HBW |

*) numbers in the designation of steel BAL and BA refer to the thickness of welded specimens in mm; information in parentheses is concerned with temperature (°C) and time (hour) of isothermal holding

Tables 1 and 2 present the chemical composition and the mechanical properties of nanobainitic steels used in the technological tests. For comparative purposes, Tables also present the chemical composition of steel Strength (Weldox) 1300 (SSAB) and Armstal 550 (HSJ).

## Test results and analysis

The research work involved the rotational friction welding of test elements (plate fragments) made of 8 mm thick steel BA8 and 13 mm thick steel BAL13 using a wire (grade C45) having a diameter of 20 mm.

The first stage involved the welding of 8 mm thick plate made of nanobainitic steel after heat treatment (steel BA8, variant 210°C/120 hours, having a hardness of 614 HV), using a bar having a diameter of 20 mm, made of structural

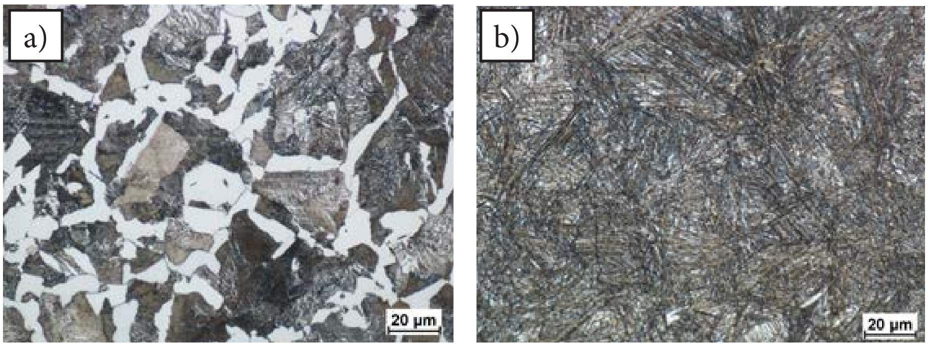


Fig. 1. Microstructure of the base material a) bar made of ferritic-pearlitic steel C45, b) plate made of bainitic steel BA 8, variant 210/120

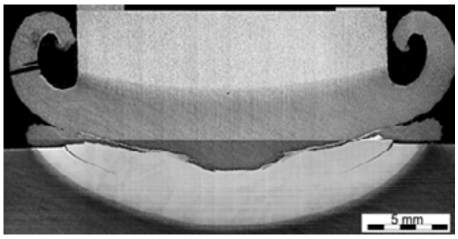


Fig. 2. Macrostructure of the friction stir-welded joint made of bainitic steel and the bar made of structural ferritic-pearlitic steel

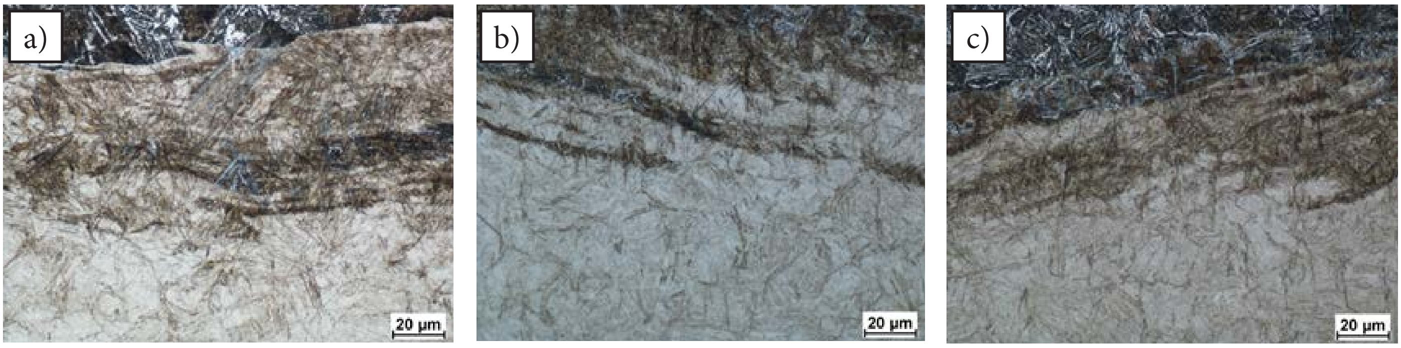


Fig. 3. Microstructure in the friction welded joint, bar made of steel grade C45, plate made of bainitic steel BA 8, variant 210/120

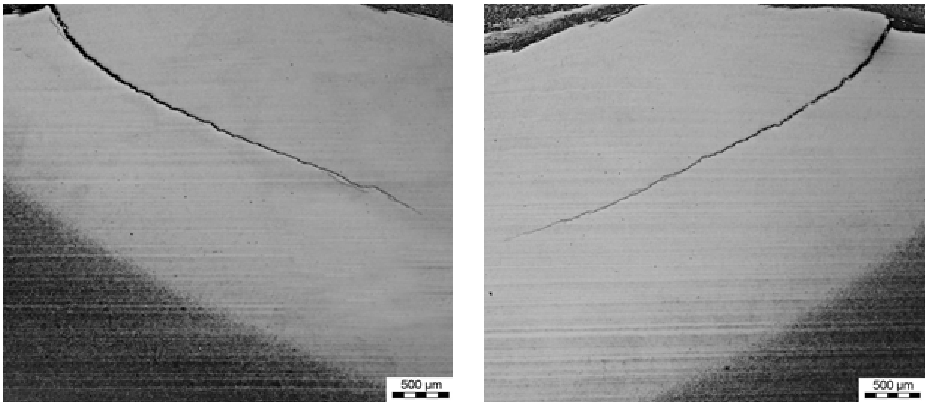


Fig. 4. Cracks in the friction welding-induced hardened zone

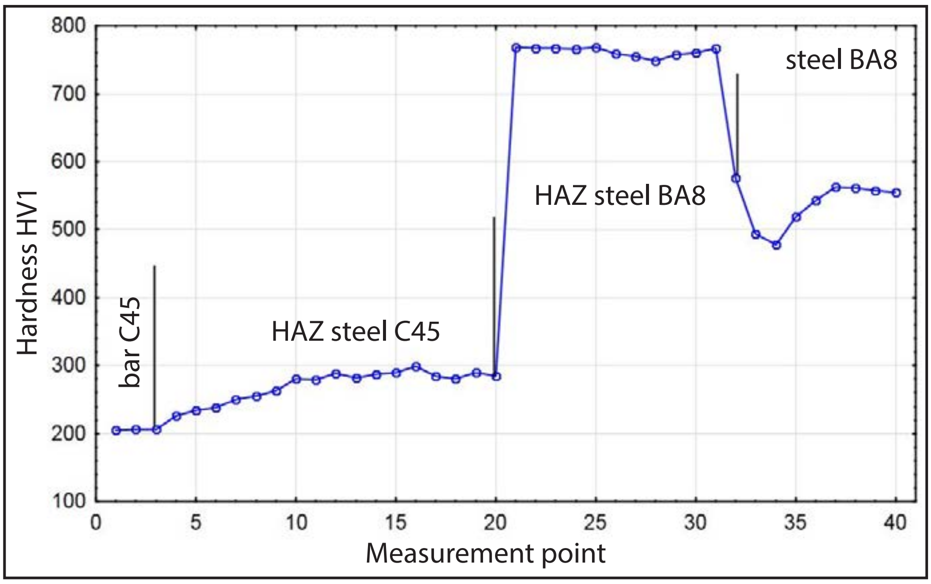


Fig. 5. Hardness measurement results concerning the friction welded joint, bar made of steel grade C45, plate made of bainitic steel BA 8, variant 210/120

steel C45 having a hardness of 205 HV. The microstructure of the base materials before welding is presented in Figure 1. In the as-received state, steel grade BA8 was characterised by the microstructure containing nanolath carbide-free bainite and retained austenite. In turn, the microstructure of steel C45 was ferritic-pearlitic. The macrostructure of the joint is presented in Figure 2. As a result of an increase in temperature, a hardened layer having the martensitic-bainitic (M+B) layer was formed in the joint area (Fig. 3). The fusion line between the bar and the plate did not reveal any microcracks. However, macrocracks were revealed in the hardened area of the HAZ (Fig. 4). Figure 5 presents a diagram showing the distribution of hardness in

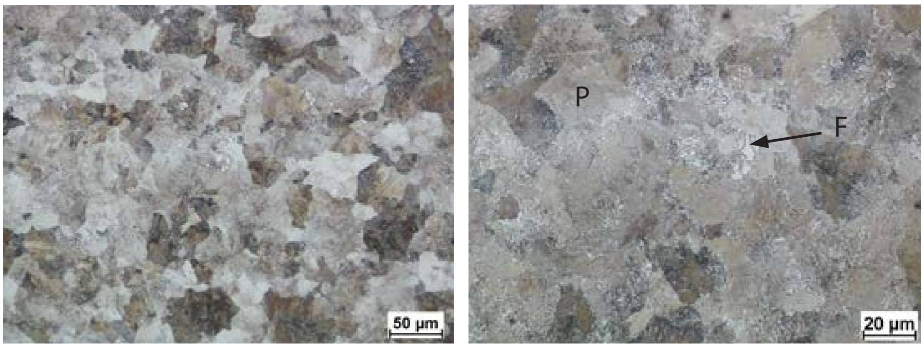


Fig. 6. Microstructure of the base material, steel BAL13, pearlitic microstructure (P) with some pre-eutectoid ferrite (F)

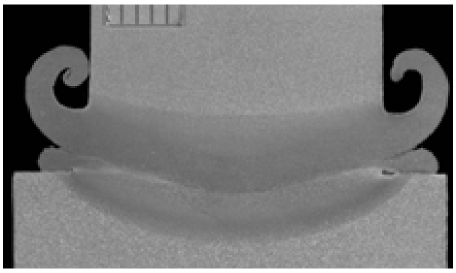

Fig. 7. Macrostructure of the friction welded joint made in nanobainitic steel BAL13 and ferritic-pearlitic structural steel C45

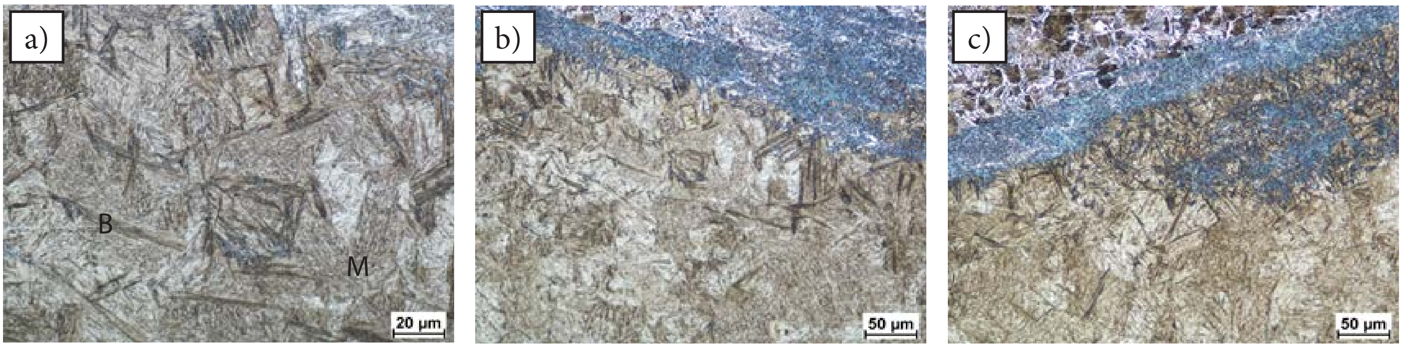


Fig. 8. Microstructure of the HAZ, steel BAL 13, martensitic-bainitic (M-B) microstructure at the interface of the materials

the welded joint. The hardness in the hardened HAZ, characterised by the martensitic microstructure, amounted to 766 HV.

Friction welding in the solid state was also used to join steel BAL13 (softened state) with steel C45. Figure 6 presents the microstructure of steel BAL13 (13 mm thick plate not subjected to heat treatment, hardness in the as-delivered state amounting to 276 HV). The steel was characterised by the pearlitic microstructure with a slight content of pre-eutectoid ferrite (Fig. 6).

The macrostructure of the joint is presented in Figure 7. The welding thermal cycle led to the formation of a hardened martensitic-bainitic layer having a hardness of 834 HV (Fig. 8, 9). The zone of the joint between the bar and the plate did not reveal the presence of microcracks. The distribution of hardness in the joint is presented in Figure 9.

The second stage of the research included TIG welding tests performed without the use of the filler metal. The identification of welding parameters was followed by the making of test joints in 5 mm and 8 mm thick plates of the nanobainitic steel (Table 2). The plates were welded in the softened state and after the final heat treatment. The joint made in the softened state was subjected to the standard post-weld heat treatment applied in cases of nanobainitic steels.

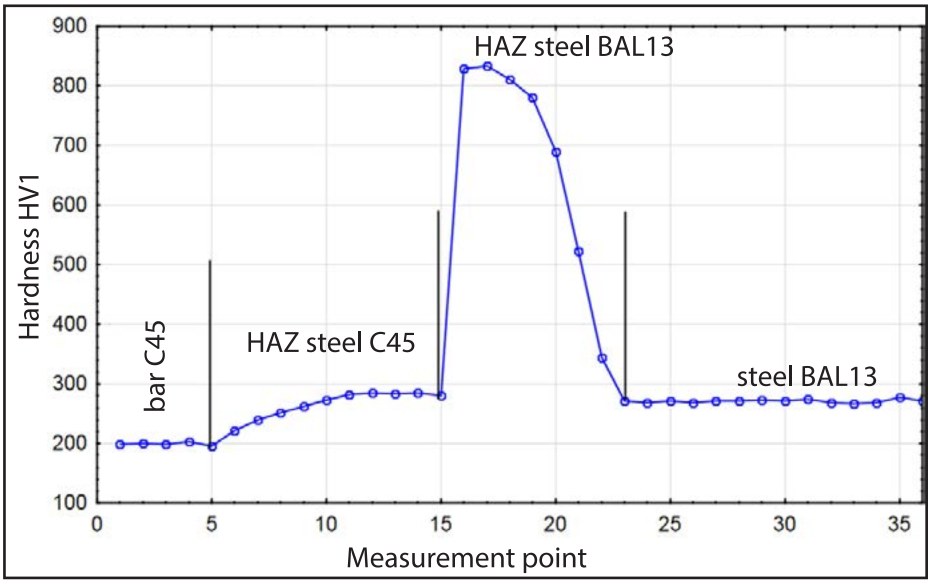


Fig. 9. Hardness distribution in the friction-welded joint made steel BAL 13 (plate) and steel C45 (bar)

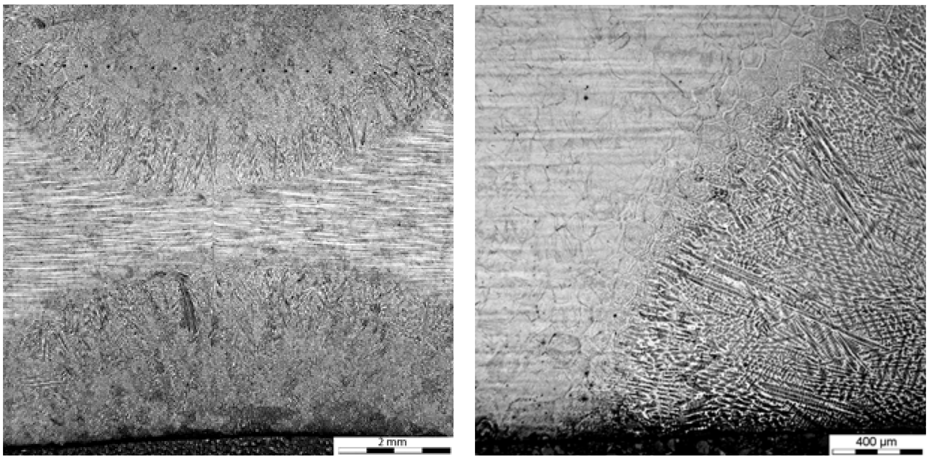


Fig. 10. Macro and microstructure in the TIG welded joint area; 8 mm thick steel plate in the softened state

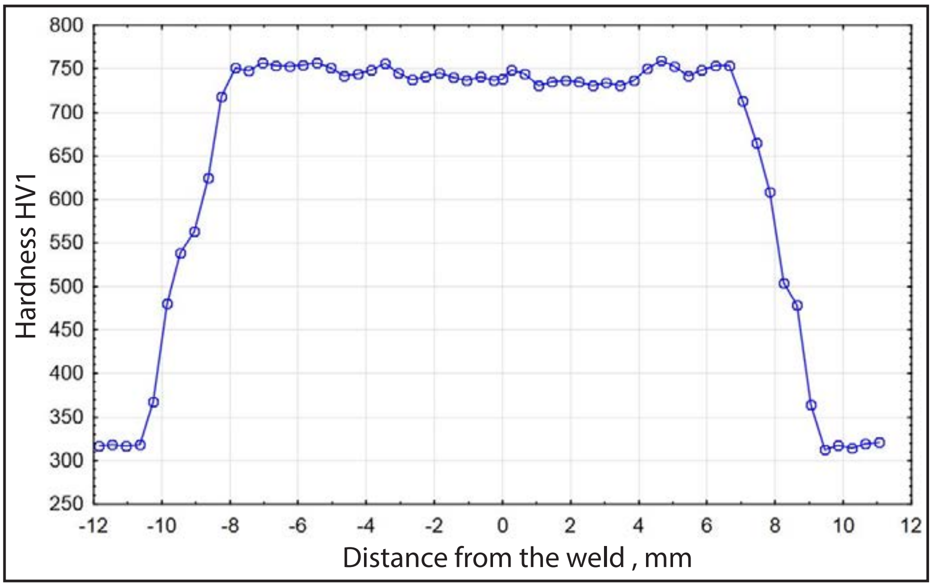


Fig. 11. Hardness measurement results and the macrostructure of the TIG-welded joint; 8 mm thick plate in the softened state - BA 8 (softened state)

Figure 10 presents the macrophotograph (macro and microstructure) of the joint made in the 8 mm thick plates of the nanobainitic steels in the softened state. The joint area did not reveal any macro or microcracks. Figure 11 presents the distribution of hardness in the weld and in the heat affected zone. The maximum hardness in the weld and in the HAZ amounted to 750 HV. To obtain required functional properties, the joint was subjected to the final heat treatment applied in cases nanobainitic steels. The above-named heat treatment involved austenitisation performed at a temperature of 950°C as well as controlled cooling and isothermal holding at a temperature of 210°C. Figure 12 presents the macrophotograph of the joint subjected to heat treatment. Following the above-named heat treatment, the joint did not contain any cracks. Microstructural tests of the weld area revealed the presence of carbide-free bainite uniformly arranged across the thickness of the joint (Fig. 13, 14). Test performed using the light microscope revealed the presence of two overlapping structures, i.e. the dendritic solidification structure characteristic of the weld and the final microstructure in the form of nanolath bainite. The presence of the carbide-free nanolath bainitic microstructure was confirmed by tests performed using the scanning electron microscope (Fig. 14). The hardness of the weld area was restricted within the range of 590 HV to 610 HV (Fig. 15), i.e. the value expected after the use of heat treatment. The cyclic fluctuations could be ascribed to the welding-induced dendritic microsegregation.

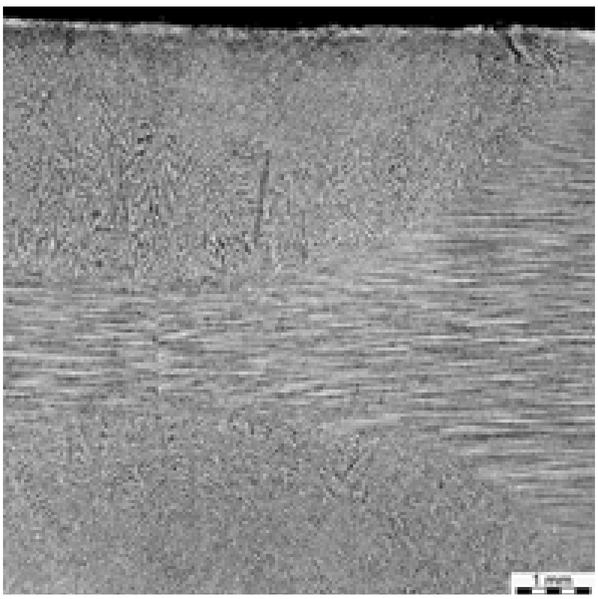


Fig. 12. Macrostructure of the TIG-welded joint made of the 8 mm thick steel plate; the plate was welded in the softened state and, afterwards, subjected to the 210/120 heat treatment

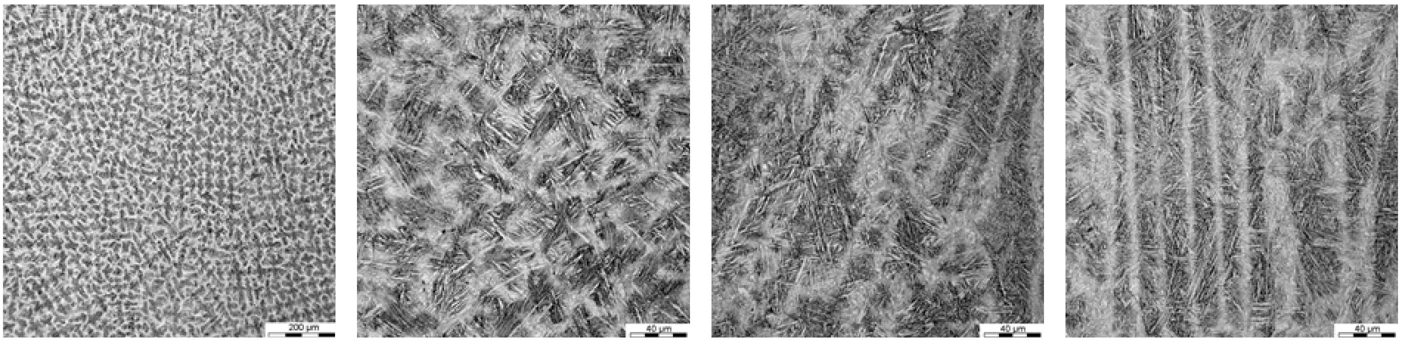

Fig. 13. Microstructure in the weld area of the TIG-welded joint made of the 8 mm thick steel plate; the plate was welded in the softened state and, afterwards, subjected to the 210/120 heat treatment 210/120; light microscope [10]

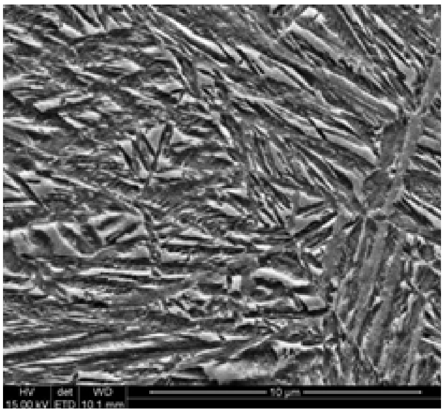

Fig. 14. Microstructure in the weld area of the TIG-welded joint made of the 8 mm thick steel plate; the plate was welded in the softened state and, afterwards, subjected to the 210/120 heat treatment 210/120; scanning electron microscope [10]

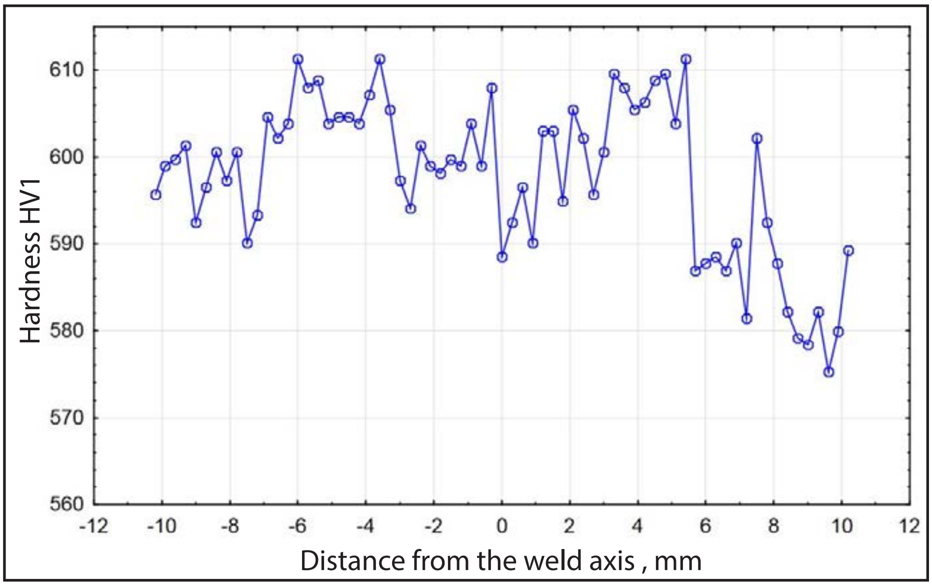


Fig. 15. Hardness measurement results and the macrostructure of the TIG-welded joint; 8 mm thick plate in the softened state and, afterwards, subjected to heat treatment - BA 8z (210/120) [10]

Figures 16 and 17 present the tests results concerning the macro and microstructure of the joint made of 5 mm thick plates respectively (after the 210/120 heat treatment and in the softened state). The weld area and the HAZ did not reveal any cracks. The weld and the zone heated (during welding) to the austenite range contained lath martensite. Figures 18 and 19 present the tests results concerning the macro and microstructure of the joint made of 8 mm thick plates after heat treatment. In spite of applying low energy, assessed on the basis of the penetration depth, the weld area contained interdendritic cracks. In the weld area that hardness amounted to approximately 720 HV. In the heat affected zone the material was tempered

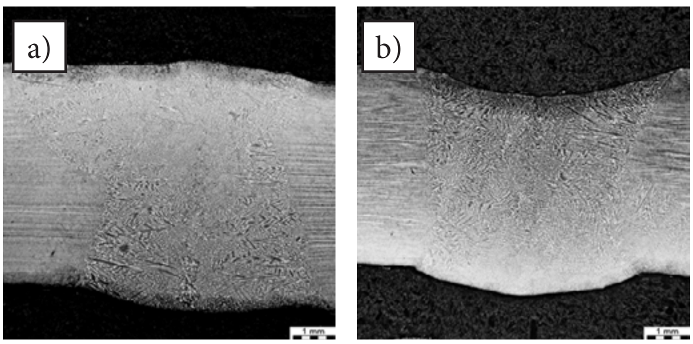


Fig. 16. Macrostructure of the TIG-welded joints made of the 5 mm thick plates; (a) plate after the 210/120 heat treatment, (b) plate in the softened state

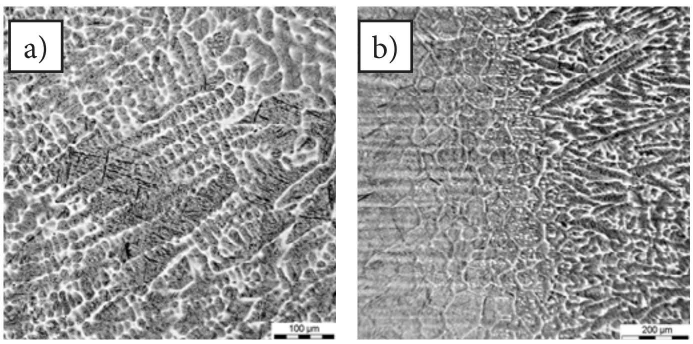


Fig. 17. Microstructure of the TIG-welded joints made of the 5 mm thick plate; (a) plate after the 210/120 heat treatment, (b) plate in the softened state

to a hardness of approximately 450 HV (Fig. 20). The high-temperature part of the HAZ underwent hardening, whereas the part heated to temperature below A1 underwent softening.

## Conclusions:

The study aimed to verify the weldability of modern high-carbon high-strength nanobainitic steels finding applications in the defence and machine-building industries. The experimental steels were developed and made at the Institute for Ferrous Metallurgy (Instytut Metalurgii Żelaza). The study-related tests justified the formulation of the following conclusions:

- in the as-delivered state and after being subjected to the final heat treatment, nanobainitic steel BA8 is characterised by the microstructure containing nanolath carbide-free bainite and retained austenite. In turn, steel BAL13 (not subjected to the final heat treatment) is characterised by the pearlitic microstructure with a slight content of pre-eutectoid ferrite;
- heat affected zone of the friction-welded joint made of steel BA8 revealed the presence of a hardened layer (766 HV) characterised by the martensitic-bainitic (M+B) structure. In turn, the heat affected zone of the friction-welded joint made of steel BAL13 also contained the martensitic-bainitic (M+B) structure, yet characterised by higher hardness (834 HV);
- TIG-welded joint made in 8 mm bainitic steel thick plates in the softened state and subjected to the final heat treatment did not reveal the presence of cracks; the weld contained nanolath carbide-free bainite uniformly arranged across the joint thickness,
- weld of the TIG-welded joint made in 8 mm bainitic steel thick plates subjected to the final

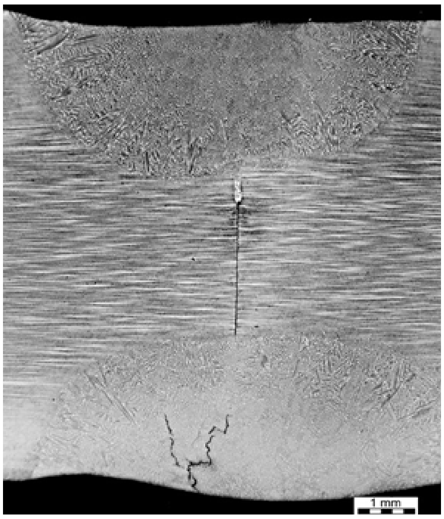


Fig. 18. Macrostructure of the TIG-welded joints made of the 8 mm thick plate; plate was welded after the 210/120 heat treatment

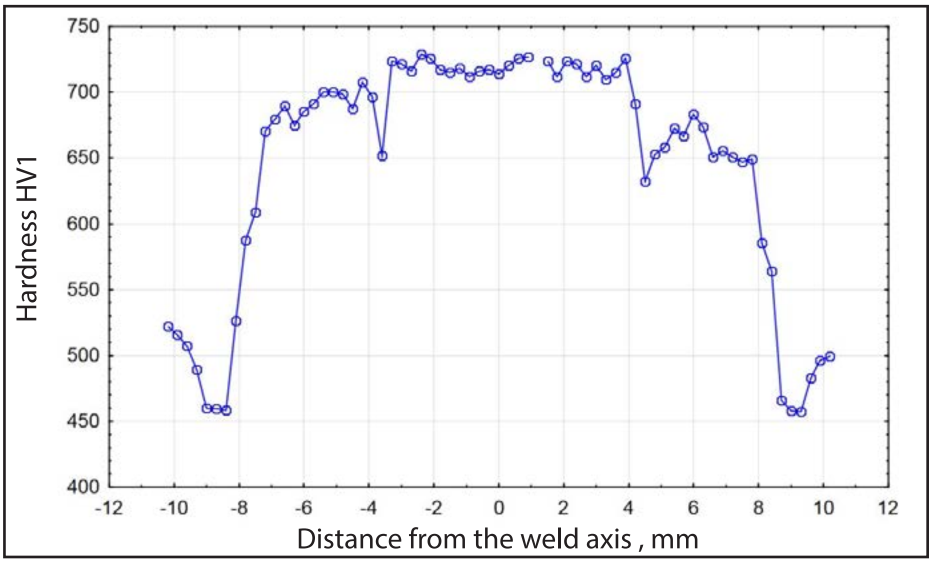


Fig. 20. Hardness measurement results and the macrostructure of the TIG-welded joint; 8 mm thick plate welded after being subjected to heat treatment - BA 8 (210/120) [10]

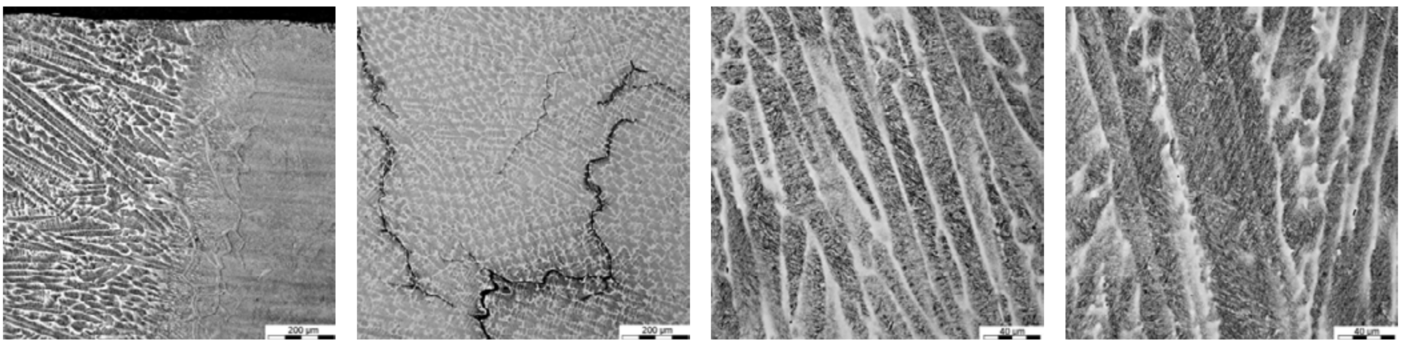

Fig. 19. Microstructure of the TIG-welded joints made of the 8 mm thick plate; plate was welded after the 210/120 heat treatment

heat treatment revealed the presence of interdendritic cracks. The hardness in the weld area amounted to approximately 720 HV, whereas that in the HAZ amounted to approximately 450 HV. The high-temperature part of the HAZ revealed hardening, whereas the part heated to a temperature below A1 was characterised by softening;

- because of their limited weldability, nanobainitic steels should be subjected to preheating at a temperature exceeding 200°C. However, the effect of higher temperatures (e.g. 300°C or 400°C) on the microstructure of the above-named steels remains to be identified;
- fusion welding and pressure welding of nanobainitic steels can be performed in the softened state. Afterwards, joints should be subjected to standard austenitisation heat treatment and direct isothermal holding.

***The above-presented study was performed within research activity financed by Instytut Spawalnictwa and the Institute for Ferrous Metallurgy.***

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