



Selected Mechanical and Technological Properties of S355J2/NANOS-BA[®] Clad Plates after Hot Rolling with Two-Stage Heat Treatment

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Abstract

The article presents the results of hot rolling tests on a feedstock composed of S355J2 and NANOS-BA[®] steel layers into flat bars. The study was carried out to assess the susceptibility of the materials to create S355J2/NANOS-BA clad plates in the hot rolled bonding process. The subject of the article are the phenomena occurring during the connection of well-weldable S355J2 structural steel with ferritic-pearlitic microstructure with nano-structured, non-weldable NANOS-BA[®] steel with nanobainitic microstructure in the process of hot rolling and heat treatment. The microstructure and selected strength properties of high-strength clad plates are described after hot rolling with integrated inter-operational annealing at 690°C for 4 h and after additional isothermal annealing at 210°C for 120 h. As a result of hot rolled bonding process with two-stage heat treatment process a durable combination of S355J2 and NANOS-BA[®] steels with high mechanical properties was obtained, including: $R_m > 1199$ MPa and $A = 14\%$, without microscopically visible cracks in the joined plane. High-strength laminated flat bars combining the features of the component layers such as high strength, ballistic and abrasive resistance, while maintaining good plasticity, weldability and relatively low production costs may be the answer to the current industry demand.

Keywords: Clad plates, Nanobainitic steel, Hot rolling bonding nanostructured steel, High-strength steels

1. Introduction

Clad plates consist of at least two layers of materials permanently connected to each other as a result of the influence of appropriately high temperature, pressure forces or vacuum [1], [2]. Laminated sheets are produced in the hot rolling process mainly in order to apply a layer with the desired properties on a base sheet carrying mechanical loads, which is often made of low-hardness steel [2], [3]. NANOS-BA[®] steel with a nanobainitic microstructure is a promising material which, due to its very high ballistic resistance, can be used in the defence industry, e.g. as one of the

layers of composite armour [4]. This steel may also be used for parts of machines or devices with the required high abrasion resistance [5], [6]. The NANOS-BA[®] steel is not weldable using classical methods, which significantly limits its use as a construction material [7]. Research is still on going in research centres to develop welding and joining techniques for products made of this type of steel [8], [9]. So far, only the technology of welding NANOS-BA[®] steel with non-weldable 42CrMo4 steel in the hot rolling process has been developed [9], and the produced 42CrMo4/NANOS-BA[®] flat bar does not provide the possibility of combining metalware with other materials using welding



techniques. The article describes attempts to produce a new generation of S355J2/NANOS-BA® flat bars in the process of hot rolling and two-stage heat treatment. The idea of the project was to combine ultra-high-strength steel with, among others, high abrasive and ballistic resistance with cheaper steel, S355J2, ensuring sufficient strength for a given application and the possibility of joining the metalware using welding techniques. The production of a laminated flat bar with a strength at least equal to currently used high-strength steels combined with the unique properties of the applied layer may be the answer to the current industry demand.

2. Material and methodology

The basic material for hot rolling tests with two-stage heat treatment was weldable structural steel S355J2 with a ferritic-pearlitic (S) microstructure. The applied material was non-weldable NANOS-BA® steel with a nanobainitic (N) microstructure. The chemical composition of the tested steels is given in Table 1, while the mechanical properties are given in Table 2.

Table 1. Chemical compositions of steel for two-layer flat bars, weight %

Material	Ingredient content, %											
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	N	V
S355J2+N	0,16	1.22	0.24	0.012	0.005	0.076	0.069	0.0250	0.153	0.033	0.010	0.0040
	Nb	Ti	C _c									
	0,0023	0.0021	0.40									
NANOS-BA®	C	Mn	Si	P	S	Cr	V	Cu	Mo	Ti	C _c	
	0,58	1.90	1.82	0.012	0.005	1.32	0.095	-	0.75	0.010	1.33	

Table 2. Mechanical properties of steel S355J2+N and NANOS-BA®

Steel grade	Yield strength	Tensile strength	Elongation
	R _{eH} , MPa	R _m , MPa	A, %
S355J2+N	428	530	28.5
NANOS-BA®	>1300	>1900	>10

For semi-industrial hot rolling tests, feedstock was prepared, consisting of layers of S355J2 and NANOS-BA® steel after mechanical surface treatment to the same dimensions: thickness 20 x width 135 x length 240 mm. The contact surfaces were degreased before joining. The layers were roughly joined using a universal welding machine using the MAG welding technique. Rough joining of the material around the circumference was primarily intended to ensure the stability of the feedstock composed of two different steels and to protect it against the interference of oxides and other impurities into the welding area during heating and

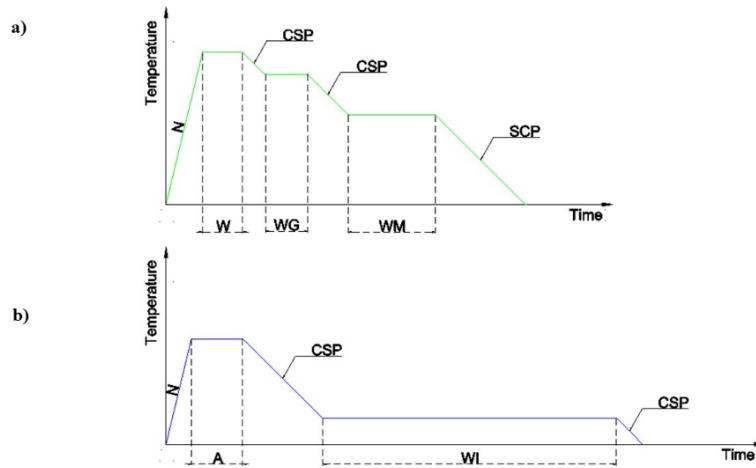
annealing of the feedstock, hot rolling and heat treatment. The two-layer feedstock was heated in a resistance heating furnace. The feedstock was loaded on a well-heated hearth into the furnace chamber heated to 100°C higher than the beginning of hot plastic forming. Temperature differences between the surface and the centre of the feedstock did not exceed 2°C. A similar range of temperature differences, i.e. ≤ 2°C, characterised the temperatures of the middle and ends of the heated feedstock. The feedstock was heated at this temperature for approximately 30 minutes. The feedstock was heated and annealed without a protective atmosphere. The technological parameters of hot rolling were selected for the process carried out on rollers with a diameter of 550 mm and their linear speed of 0.20 m/s. Depending on the variant implemented, the two-layer feedstock was rolled into flat bars each time in one pass, with different deformation ranging from 10% to 40% and different hot rolling start temperatures ranging from 800°C to 1100°C, Table 3.

Table 3. List of laminated feedstock for hot rolling into S355J2/NANOS-BA® two-layer flat bars, along with heat treatment procedures planned after hot working

Identification of feedstock/clad plates	Temperature of start of hot plastic working, °C	Draft in one pass, %	Cooling immediately after hot rolling (Stage 1.)	Additional heat treatment (Stage 2.)
S+N nr 1	800	10	Inter-operational annealing	-
S+N nr 2	800	20		-
S+N nr 3	900	10		-
S+N nr 4	900	20		-
S+N nr 5	900	30		-
S+N nr 6	1000	10		-
S+N nr 7	1000	20		-
S+N nr 8	1000	30		-
S+N nr 9	1100	10		-
S+N nr 10	1100	20		-
S+N nr 11	1100	30		-
S+N nr 12	1100	40		-
S+N nr 13	1100	40		Isothermal annealing

After the hot rolling process, all flat bars were subjected to inter-operational annealing (softening) using the heat from the rolling process. Inter-operational annealing was carried out at 690°C with a holding time of 4 h and subsequent slow cooling with the furnace to ambient temperature – stage 1. Then, samples taken from selected flat bars in the softened state were subjected to additional heat treatment – stage 2: austenitising at 940°C with a holding time

of 40 minutes and final isothermal annealing with controlled bainitic transformation of the NANOS-BA® steel. Isothermal annealing was carried out at 210°C for 120 h, Fig. 1. The main criterion for selecting this variant of the final heat treatment was the possibility of obtaining high mechanical properties with high ballistic resistance [10] and resistance to abrasive wear [6] in the applied layer of the NANOS-BA® steel.



N – heating the feedstock to a temperature within the range of 900-1200°C, W – annealing the feedstock at a temperature in the range of 900-1200°C for 30 min, A – austenitising (annealing) of samples at 940°C for 40 min, WG – hot rolling, WM – inter-operational annealing at 690°C for 4 h, then cooling with the furnace to ambient temperature, WI – isothermal annealing at 210°C for 120 h, CSP – free cooling in the air, SCP – slowed cooling with the furnace.

Fig. 1. Subsequent technological stages of producing S355J2/NANOS-BA® flat bars in the hot rolling process with two-stage heat treatment: a) hot rolling with integrated inter-operational annealing – stage 1, b) 2 additional heat treatment with isothermal annealing – stage 2.

In order to assess the quality of the manufactured S355J2/NANOS-BA® joints, laboratory tests were performed on samples taken from semi-finished products (after inter-operational annealing) and final products (after isothermal annealing). The laboratory tests included: light microscopy, scanning electron microscopy, static tensile test and shear strength test. Due to the lack of an appropriate standard for strength tests of joints made of the S355J2 and NANOS-BA® steels, the study involved tensile and shear tests using a Zwick/Z250 universal testing machine with a maximum load of 250 kN. The static tensile test at room temperature was carried out in accordance with the PN-EN ISO 6892-1 standard. Shear resistance tests were carried out based on the guidelines of the Chinese standard GB/T6396-2008, Fig. 2.

Preparing samples for shear resistance tests requires very precise drilling of grooves to a depth right next to the place where the layers are welded. In the event of inaccurate sample preparation, the test result should be treated as inaccurate or incorrect. A constant groove width of 8 mm was assumed for all samples in this study. In the case of the macroscopically visible welding plane of S355J2 and NANOS-BA® steel, precise grooves were made by milling to the visible welding point. The adopted dimensions were compared with the layer thicknesses determined in microscopic tests. In the absence of a visible welding plane, the depth of the grooves was determined based on the thicknesses of individual layers obtained for the appropriate flat bars in microscopic tests.

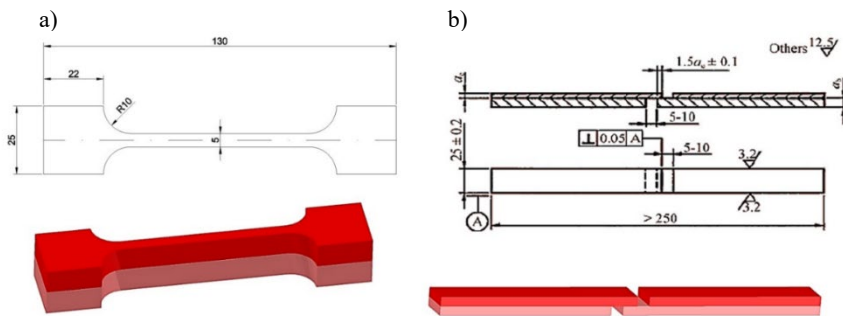


Fig. 2. Two-layer samples intended for: a) tensile tests, b) shear strength tests acc. to the GB/T6396-2008 standard

3. Results and discussion

Physical tests of hot rolling of the S355J2/NANOS-BA® feedstock into flat bars were carried out in a 2-high reversible rolling mill at Łukasiewicz Research Network – Upper Silesian Institute of Technology. The rotational speed of the upper and lower rollers during semi-industrial tests was the same and amounted to 6 revolutions/min. After hot rolling and inter-operational annealing, the strips were cut longitudinally along the symmetry axis of the strip. The surface near the welding plane (the place where two steels meet) was assessed using a light microscope. It was assumed that the basic criterion determining the

possibility of complete welding of two layers was the complete absence of voids, cracks, delamination or other material discontinuities near the welding plane. Based on the observations of the microstructure, the defects occurring in the material were classified depending on the steel joining technology, Fig. 3. As a result of hot rolling with a draft in the range of 10-20% at 800-900°C, no welding of the sheets was achieved, and the strips fell apart after cutting, Fig. 3a. As a result of rolling the strips at 1000°C with a deformation of 10-30%, partial welding of the layers occurred only around the middle of the strips, Fig. 3b. During rolling at 1100°C with a deformation of 10-30%, the layers were joined together with visible signs of lack of complete welding in the form of voids in the welding plane, Fig. 3c.

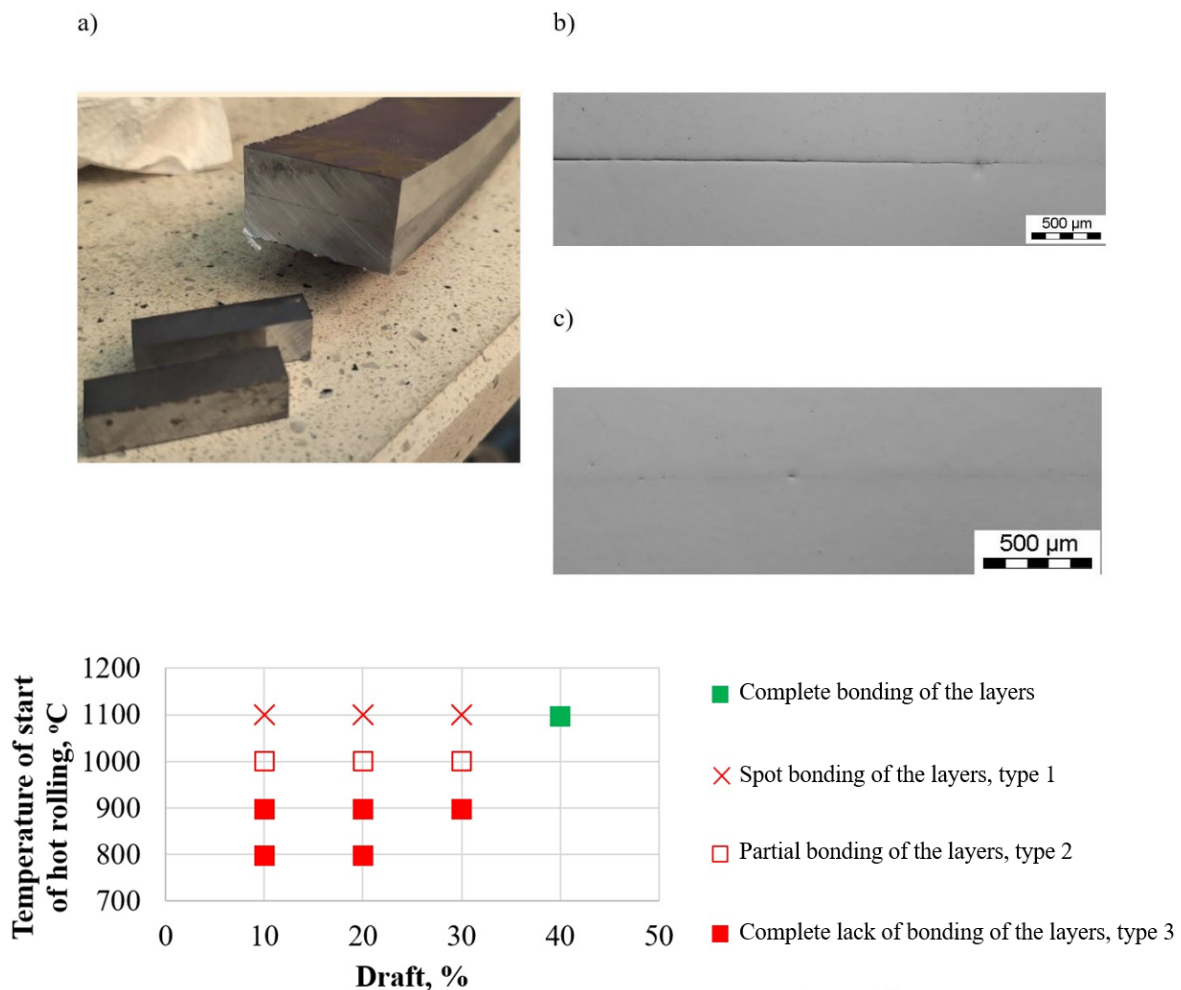


Fig. 3. Photographs and classification of the type of defects occurring in the welding plane of S355J2/NANOS-BA® flat bars after hot rolling with variable process parameters: a) type 3, complete lack of bonding of the layers, type 1, spot lack of bonding, b) type 2, partial bonding of the layers, visible delamination at the edges of the strip and c) visible voids in the bonding plane

Based on macro and microscopic tests, it was found that the materials were fully welded only after hot rolling of the flat bar S+N No. 12 in one pass with a deformation of 40% and a rolling

start temperature of 1100°C. The maximum metal pressing force on the rollers was 0.9 MN. The registered pressure forces and rolling torque during the rolling tests are shown in Figure 4.

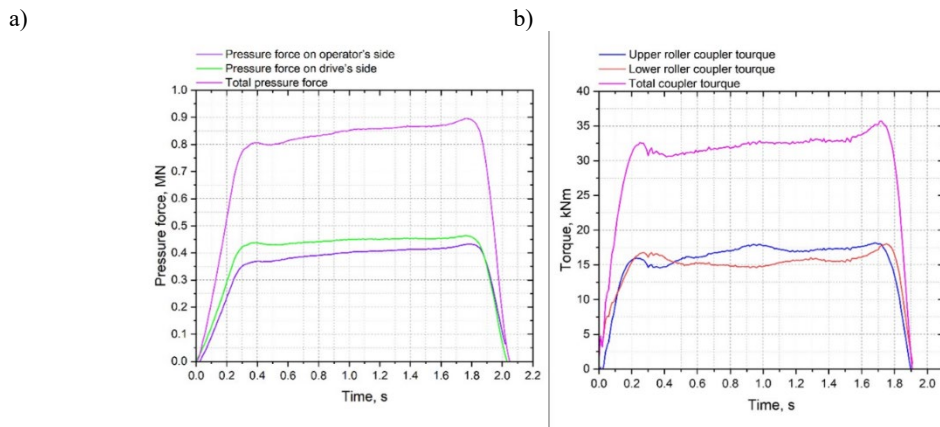
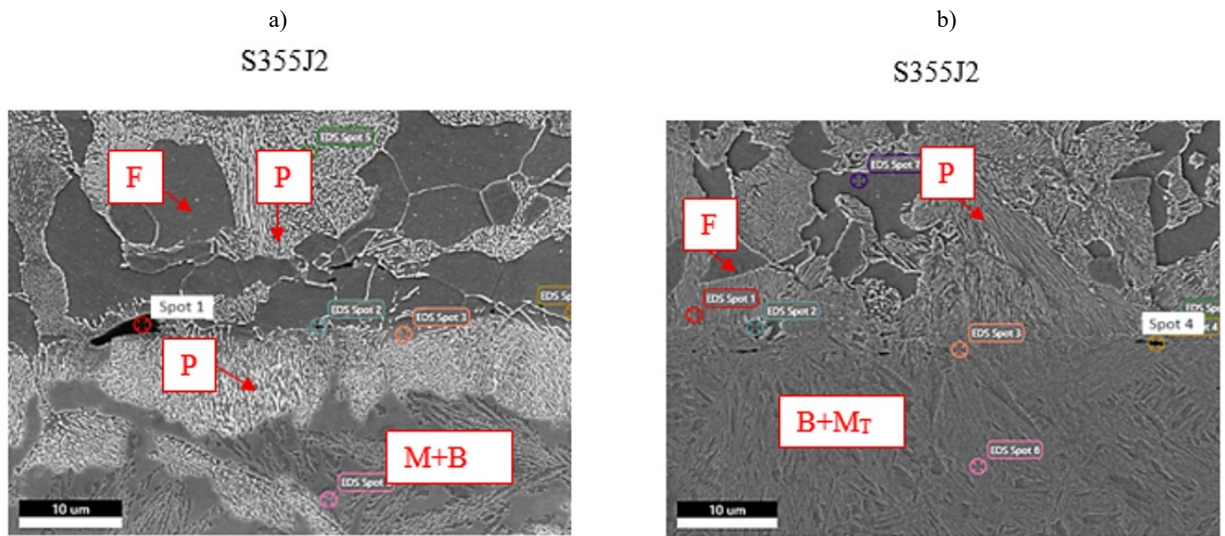


Fig. 4. Value of a) pressure force of steel on the rollers and of b) rolling torque recorded during hot rolling of the S355J2 / NANOS-BA[®] two-layer flat bar in one pass with a 40% deformation

Structure observations carried out using an Olympus DSX500 light microscope and an Inspect F scanning electron microscope on microsections taken from the S+N flat bar No. 12 did not reveal any cracks or other discontinuities throughout the entire cross-section and longitudinal section of the flat bar. In the welding plane, there are only numerous, small, single oxide inclusions with a width of up to approx. 10 μm in the form of Fe, Mn, Si and Al oxides. These are mainly surface oxidation products and residues from the feedstock preparation process, Fig. 5. The microstructure after inter-operational annealing in the parent material – NANOS-BA[®] steel – was a mixture of martensite, bainite and pearlite, Fig. 6a. Near the welding plane, on the S355J2 steel side, the microstructure was ferritic-pearlitic with visible banding, while on the NANOS-BA[®] steel side, it was composed of martensite and bainite with a small share of pearlite 5a. As a result of additional isothermal annealing of the S+N joint No. 13 in the NANOS-BA[®] steel parent material, a homogeneous nanobainitic microstructure with the assumed high strength was obtained, Fig. 6b. A similar morphology of bainite was also confirmed for high carbon nanobainitic steel after controlled thermomechanical treatment at works [11], [12]. Two-phase bainitic–austenitic microstructure was obtained in the parent material, typical for this type of steel [13]. Near the welding plane of the isothermally heated joint, on the NANOS-BA[®] steel side, there is a nanobainitic microstructure with numerous areas of tempered martensite. In this area microstructure is similar to the typical microstructure of the NANOS-BA[®] steel after cooling from austenite field (950 $^{\circ}\text{C}$) to the temperature of isothermal transformation (approx. 185 $^{\circ}\text{C}$) at the rate of 10 $^{\circ}\text{C}/\text{s}$ [14, 15], while on the S355J2 steel side, a carburised pearlite-ferritic microstructure was observed, Fig. 5b.

The bond strength between two layers of materials is most important for all mechanical properties of laminated sheets [3]. The samples made for strength tests consisted of two layers of steel with different mechanical properties, therefore the stresses in both layers

were different and the resulting graphs were non-standard. The distance in millimetres measured by the extensometer is shown on the abscissa, and the force in kilonewtons is shown on the ordinate. The test results in the form of sample diagrams obtained in the tensile and shear strength tests are presented in Figs. 7 and 8, respectively. As a result of hot rolling in one pass with 40% deformation with integrated inter-operational annealing, the minimum tensile strength of the joint was obtained at the level of 900 MPa, with low total elongation at room temperature of 3.2%. As a result of additional heat treatment with isothermal annealing, the tensile strength of the joint was increased by almost 300 MPa, with a simultaneous increase in the total elongation to approximately 14%, Table 4. The minimum shear strength of the S+N flat bar after inter-operational annealing was 135 MPa. As a result of additional isothermal annealing, the minimum shear strength of the joint was more than doubled to 295 MPa, Table 5. For S355J2/NANOS-BA[®] clad plates shear strength was lower than nanostructured bainitic steels [16]. During the shear strength test, each time the material ruptured outside the welding plane in a layer of lower-strength steel. The obtained results indicate very good welding of both layers in both variants of final heat treatment and the shear strength of the joints in the welding plane is higher than the strength of a single layer. The obtained lower shear resistance and greater dispersion of the obtained values are caused by the non-uniform martensitic-bainitic-pearlitic microstructure generated in the NANOS-BA[®] steel layer after the final inter-operational annealing. As a result of additional heat treatment with isothermal transformation of the NANOS-BA[®] steel layer into a homogeneous nanobainitic microstructure, a significant increase in the strength of the joint and a smaller dispersion of the obtained results were achieved.



NANOS-BA [®]			NANOS-BA [®]		
Area 1 (Spot 1)	Weight, %	Atomic, %	Area 1 (Spot 1)	Weight, %	Atomic, %
Element			Element		
O	36.44	58.20	O	15.95	35.98
Mg	0.23	0.25	Na	0.51	0.80
Al	6.65	6.30	Mg	0.29	0.43
Si	18.58	16.90	Al	6.34	8.59
Mo	0.30	0.08	Si	6.68	8.59
Cl	0.30	0.22	Mo	0.27	0.10
K	0.36	0.24	K	0.23	0.21
Ca	3.12	1.99	Ca	0.86	0.78
Ti	1.02	0.55	Ti	0.27	0.20
Mn	24.90	11.58	Mn	6.89	4.53
			Fe	61.29	39.61

Fig. 5. Microstructure in the area of the welding plane of the S355J2/NANOS-BA[®] two-layer flat bar: a) S+N No. 12 and b) S+N No. 13, along with test locations and selected chemical composition analysis results

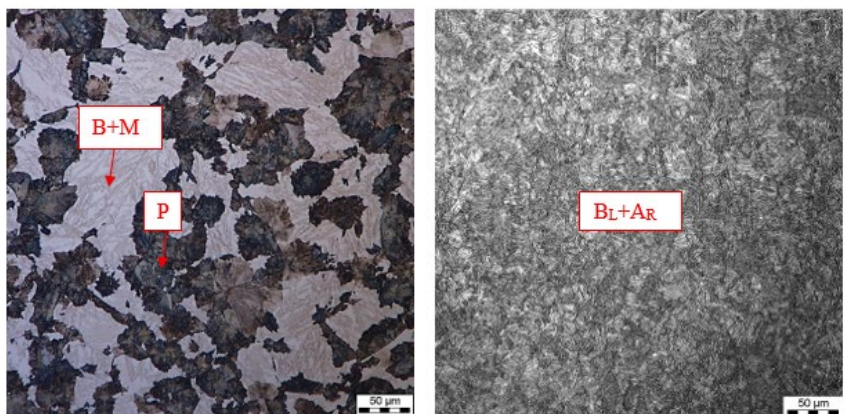


Fig. 6. Microstructure of the S355J2/NANOS-BA[®] flat bar in the middle of the NANOS-BA[®] steel layer after: a) intermediate annealing and b) isothermal annealing, LM, section etched with 4% nital

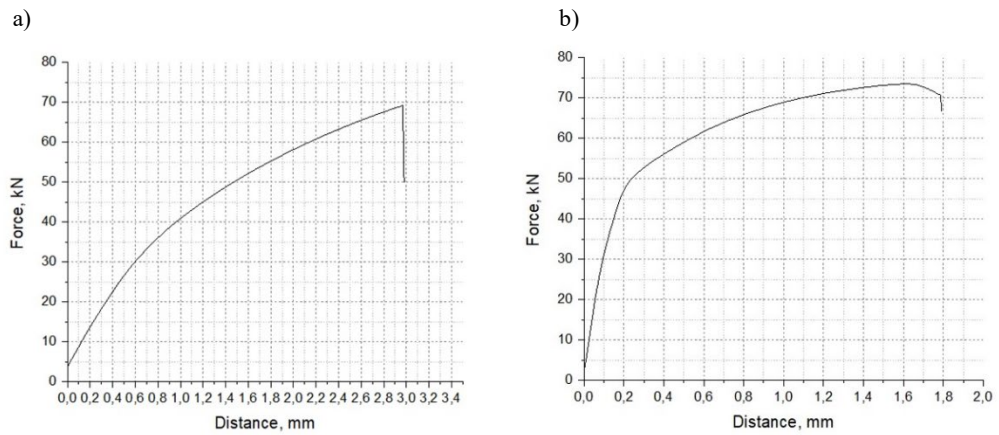


Fig. 7. Tensile test diagrams of exemplary two-layer samples taken from flat bar a) S+N No. 12 and b) S+N No. 13

Table 4.

Results of tensile strength tests of two-layer flat bars after hot rolling in the LPS line and after inter-operational annealing and additional isothermal annealing

Flat bar identification	Final heat treatment	Yield strength	Tensile strength	Elongation
		$R_{p0.2}$, MPa	R_m , MPa	A, %
S+N No. 12	Inter-operational annealing	441-514	912-916	3.2-5.1
S+N No. 13	Isothermal annealing	518-600	1199-1239	14.0-14.7

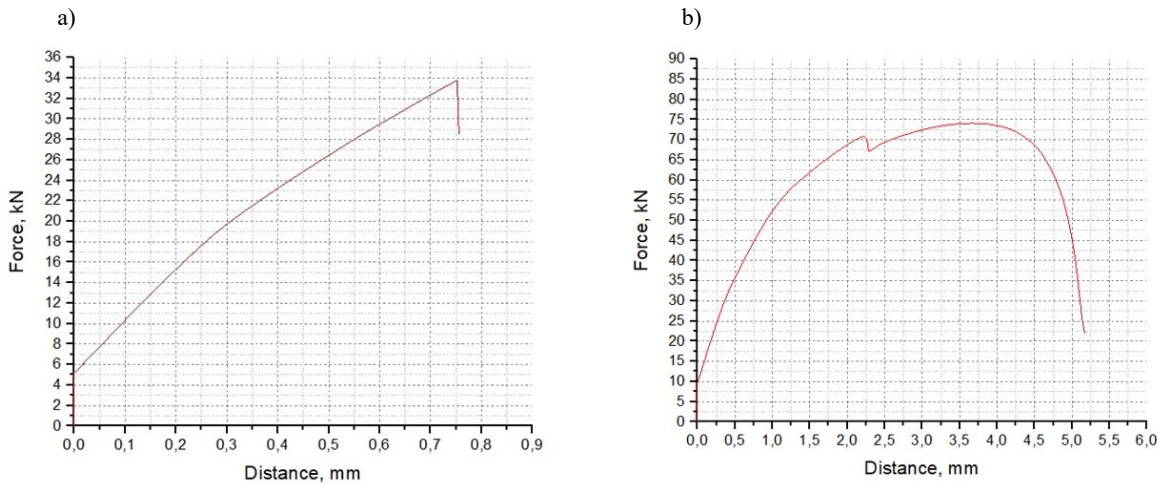

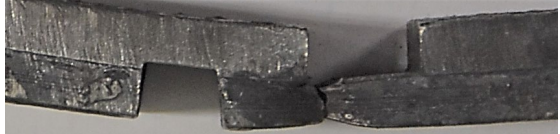


Fig. 8. Tension shear diagrams for exemplary samples taken from flat bar a) S+N No. 12 and b) S+N No. 13

Table 5.

Tensile shear strength test results for S355J2/NANOS-BA[®] plated flat bars, according to GB/T6396-2008

Clad plates identification	Shearing force	Tensile shear strength	Shear location
	f_z	R_s	
	kN	MPa	
S+N No. 12	33.7-51.3	135-209	<p><i>Applied layer: NANOS - BA[®]</i></p>  <p><i>Base layer: S355J2</i></p>
S+N No. 13	74.2-78.4	295-315	<p><i>Applied layer: NANOS - BA[®]</i></p>  <p><i>Base layer: S355J2</i></p>

4. Conclusions

As a result of hot-rolling tests carried out in one pass with a deformation of 40% at 1100°C with integrated inter-operational annealing, layers of S355J2 and NANOS-BA[®] steel were joined into one flat bar without visible discontinuities and signs of lack of welding in the welding plane. As a result of additional heat treatment with isothermal annealing according to the 210°C/120 h variant, the minimum strength and plastic properties of the S355J2/NANOS-BA[®] joint were increased to the following values: $R_{p0.2} = 518$ MPa, $R_m = 1199$ MPa, $R_t > 295$ MPa and $A = 14.0\%$. In the base material of the NANOS-BA[®] steel layer, a nanobainitic microstructure typical of this grade was obtained, with assumed high strength, ballistic resistance and abrasion resistance.

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