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STUDY ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF 42CrMo4/NANOS-BA® HIGH-STRENGTH CLAD PLATES AFTER THE PROCESS OF HOT ROLLING AND TWO-STAGE HEAT TREATMENT WITH ISOTHERMAL TRANSFORMATION

BADANIA WŁAŚCIWOŚCI MECHANICZNYCH I MIKROSTRUKTURY WYSOKOWYTRZYMAŁYCH PŁASKOWNIKÓW DWUWARSTWOWYCH 42CrMo4/NANOS-BA® PO PROCESIE WALCOWANIA NA GORĄCO I DWUETAPOWEJ OBRÓBCE CIEPLNEJ Z PRZEMIANĄ IZOTERMICZNĄ

The aim of the study was to develop a technology for welding non-weldable 42CrMo4 and NANOS-BA® steel grades in the process of hot rolling and two-stage heat treatment. As a result of physical experiments carried out in a line for semi-industrial simulation of the production of metals and their alloys (LPS) and additional heat treatment, a durable combination of 42CrMo4 and NANOS-BA® steels with high mechanical properties was obtained, including: $R_{p0.2}$ = 1036 MPa, R_m = 1504 MPa and A = 10.9%, without microscopically visible cracks and other discontinuities in the joined surface. The quality of the 42CrMo4/NANOS-BA® clad plates produced in this way was assessed on the basis of microstructure examination as well as bending, shear and tensile strength tests.

Keywords: *clad plates, hot rolling bonding, nanostructured steel*

Celem pracy było opracowanie technologii zgrzewania niespawalnych stali w gatunkach 42CrMo4 i NANOS-BA® w procesie walcowania na gorąco i dwuetapowej obróbki cieplnej. W wyniku fizycznych eksperymentów przeprowadzonych w linii do półprzemysłowej symulacji wytwarzania metali i ich stopów (LPS) i dodatkowej obróbki cieplnej uzyskano trwałe połączenie stali 42CrMo4 i NANOS-BA® o wysokich właściwościach mechanicznych m.in.: $R_{p0,2}$ = 1036 MPa, R_m =1504 MPa i A = 10,9%, bez widocznych mikroskopowo pęknięć i innych nieciągłości w płaszczyźnie zgrzewania. Ocenę jakości wykonanych tym sposobem połączeń płaskowników dwuwarstwowych 42CrMo4/NANOS-BA® dokonano w oparciu o badania mikrostruktury i próby wytrzymałości na zginanie, ścinanie i rozciąganie.

Słowa kluczowe: *blachy platerowane, zgrzewanie poprzez walcowanie na gorąco, stal nanostrukturalna*

1. INTRODUCTION

One of the main reasons for the interest of research centres in the development of technologies for the production of new layered materials is the possibility of obtaining unique functional properties for this type of product. Welding steels with a carbon equivalent C_{eq} ≥ 0.45 (difficult to weld, prone to cracking) using traditional methods does not guarantee obtaining the necessary operational properties of welded joints [1]. Joining non-weldable NANOS-BA® steels (C_{eq} = 1.34) with other steel grades using standard welding methods is currently not possible [2]. An alternative solution is the possibility of welding layers of non-weldable 42CrMo4 and NANOS-BA® steel grades together in the process of hot rolling and two-stage heat treatment. The high mechanical properties of the experimental NANOS-BA® steel, including $R_{p0.2}$ = 1315 MPa, R_m = 2103 MPa and A = 14.3% create potential for the use of this grade, e.g. in the mining or defence industry [3, 4]. The possibility of using NANOS-BA® steel in the form of a layer applied to structural steel may extend the scope of its application. Currently, the literature does not present the results of tests of joining 42CrMo4 and NANOS-BA® steels in the process of hot rolling and heat treatment. This study is a continuation of the research carried out at the Łukasiewicz Research Network – Institute of Ferrous Metallurgy (Łukasiewicz – IMŻ) on the possibility of producing high-strength clad plates, composed of layers of the experimental NANOS-BA® steel grade. The conducted experiments of welding various grades of steel together in the hot rolling

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process at Łukasiewicz – IMŻ in 2018–2019 resulted in the development of a preliminary technology for joining layers of 42CrMo4 and NANOS-BA® steels. As a result of the tests, a technology was developed that allows to obtain the following mechanical properties of 42CrMo4/NANOS-BA® clad plates: $R_{p0.2}$ = 590 MPa, R_m = 1056 MPa and A = 2% in the condition after hot plastic processing in one pass with a relative draft of ~40% and intermediate (softening) annealing [5, 6]. The study proposes new variants of hot rolling of 42CrMo4/NANOS-BA® clad plates and attempts to optimize the microstructure while increasing the functional properties of clad plates through the use of additional, controlled isothermal annealing with phase transformation of NANOS-BA® steel into nanostructured bainite with an assumed very high strength.

2. MATERIAL AND METHODOLOGY

The research material consisted of clad plates, composed of 42CrMo4 and NANOS-BA® steel layers. The basic material was commercial, non-weldable 42CrMo4 steel. The applied material was experimental, non-weldable NANOS-BA® steel. The chemical compositions of the steels used for the layers of 42CrMo4/NANOS-BA® clad plates and their selected mechanical properties after heat treatment are presented in Tables 1 and 2, respectively.

Before hot rolling bonding, the clad plates made of the 42CrMo4 and NANOS-BA® steel grades were mechanically machined to the same final dimensions: thickness 10 mm × width 140 mm × length 240 mm. The layers were degreased on contact surfaces and then joined together into packages (two-layer input) with a thickness of 20 mm each.

Attempts to join 42CrMo4 and NANOS-BA® steel layers were carried out in the hot rolling process in a line for semi-industrial simulation of the production of metals and their alloys (LPS) at the Łukasiewicz Research Network – Institute of Ferrous Metallurgy. The two-layer input was heated in a heating chamber furnace to a temperature 100°C higher than the temperature planned for the beginning of plastic processing, and then hot rolled into clad plates, according to the following variants:

- in one pass, with a ~40% reduction ratio (variant 1),
- in two passes, with a ~30% reduction ratio each (variant 2),
- in three passes, with a ~30% reduction ratio each (variant 3).

Slow cooling was applied in order to reduce the possibility of cracking during cooling of the 42CrMo4/NANOS-BA® clad plates after hot plastic processing. For this purpose, immediately after rolling, the clad plates were loaded into a furnace heated to 690°C, annealed for 4 hours, and then cooled, together with the furnace, to ambient temperature. In the next stage, additional heat treatment was performed on the samples taken from the clad plates marked with the symbols S1, S2 and S3, which shaped the final mechanical properties of the layers of NANOS-BA® steel as a result of the phase transformation of austenite into nano-structured bainite. The additional heat treatment included austenitisation of the samples at 940°C for 40 minutes, subsequent isothermal annealing in a furnace chamber at 210°C for 120 hours, and finally free cooling in air. Table 3 presents a list of materials joined into clad plates No. S1, S2 and S3 along with appropriate variants of hot plastic processing and two-stage heat treatment.

The quality of the manufactured connections of the 42CrMo4 and NANOS-BA® steels in the hot rolling process with direct intermediate annealing and additional heat treatment was evaluated in bending, tensile and shear strength tests as well as in metallographic tests. The samples for testing mechanical properties and microstructure were taken from clad plates in the direction of rolling (longitudinal samples).

The guidelines for the bending test were adopted on the basis of the PN-EN ISO 7438 standard [7] and dependence (1).

$$l = (D + 3a) \pm a/2 \tag{1}$$

where:
l – distance between supports, [mm]
D – diameter of the shaft and support rollers, [mm]
a – thickness of the layered or monolithic sample, [mm].

Table 1. Chemical compositions of steel layers intended for clad plates, [weight %]
Tabela 1. Składy chemiczne stali przeznaczonych na płaskowniki platerowane, [% masowe]

Material ■ Materiał	Component content ■ Zawartość składnika													
42CrMo4	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	N	V	Nb	Ti	C_{eq}
	0.40	0.68	0.26	0.014	0.004	0.934	0.070	0.2030	0.122	0.032	0.008	0.003	0.0034	0.0019	0.75
NANOS-BA®	C	Mn	Si	P	S	Cr	V	Cu	Mo	Ti	C_{eq}				
	0.58	1.90	1.82	0.012	0.005	1.32	0.095	–	0.75	0.010	1.34–1.4				

Table 2. Mechanical properties of steels for clad plates
Tabela 2. Właściwości mechaniczne stali przeznaczonych na płaskowniki platerowane

Steel grade ■ Gatunek stali	Variant of isothermal heat treatment ■ Wariant obróbki cieplnej izotermicznej	Yield strength ■ Granica plastyczności	Tensile strength ■ Wytrzymałość na rozciąganie	Total elongation ■ Wydłużenie całkowite	Ratio ■ Współczynnik
		$R_{p0.2}$, [MPa]	R_m, [MPa]	A, [%]	$R_{p0.2}/R_m$
42CrMo4	–	610	924	13.8	0.66
NANOS-BA®	210/120	1315	2103	14.3	0.63
	275/120	1250	1713	18.8	0.73

Table 3. List of materials intended for clad plates with variants of hot rolling and heat treatment to which they were subjected

Tabela 3. Zestawienie materiałów przeznaczonych na płaskowniki warstwowe wraz z wariantami walcowania na gorąco i obróbki cieplnej, którym zostały poddane

No. ■ Lp.	Sign of clad plates ■ Oznaczenie płaskownika platerowanego	Base layer ■ Warstwa podstawowa	Cladding layer ■ Warstwa nakładana	Stage 1. direct heat treatment ■ Etap 1. obróbka cieplna bezpośrednio po walcowaniu na gorąco	Stage 2. additional the heat treatment ■ Etap 2. dodatkowa obróbka cieplna
Variant 1, in one pass, with a ~40% reduction ratio ■ Wariant 1, jeden przepust z gniotem względnym ~40%				Softening annealing [1)] ■ Wyżarzanie zmiękczające [1)]	Isothermal annealing [2)] ■ Wyżarzanie izotermiczne [2)]
1	S1	42CrMo4	NANOS-BA®		
Variant 2, in two passes, with a ~30% reduction ratio each ■ Wariant 2, dwa przepusty z gniotem względnym ~30% każdy					
2	S2	42CrMo4	NANOS-BA®		
Variant 3, in three passes, with a ~30% reduction ratio each ■ Wariant 3, trzy przepusty z gniotem względnym ~30% każdy					
3	S3	42CrMo4	NANOS-BA®		

1) 690°C/4 h and then cooled, together with the furnace, to ambient temperature ■ według wariantu: 690°C/4 h, z następnym studzeniem w piecu do temperatury otoczenia

2) 940°C for 40 minutes and 210°C for 120 hours, and finally free cooling in air ■ 950/40 min + 210°C/120 h, z następnym chłodzeniem swobodnie w powietrzu

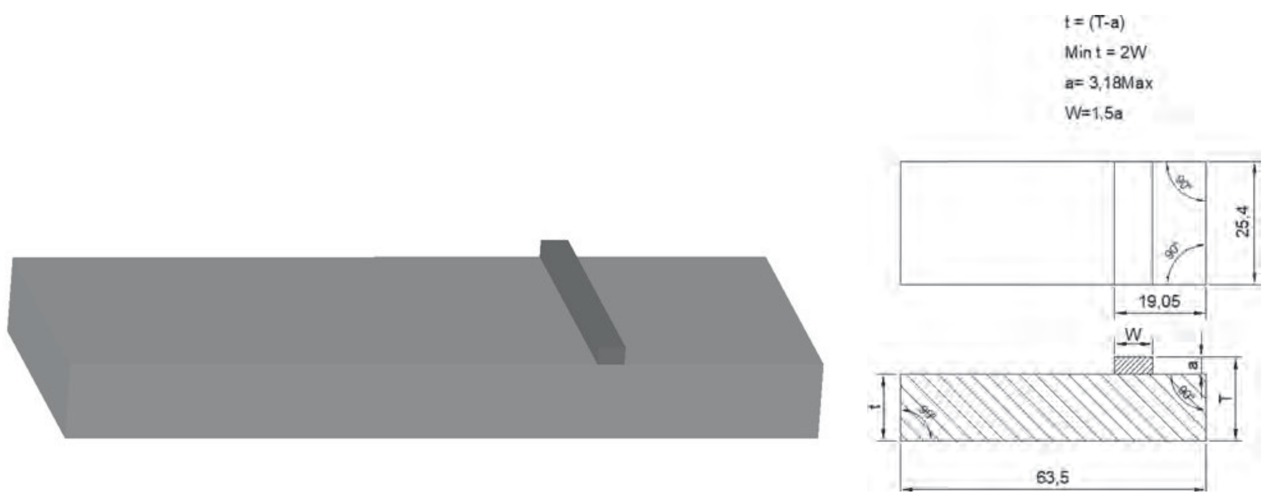


Fig. 1. Diagram of sample for shear strength tests according to the ASTM A264 standard

Rys. 1. Schemat próbki do badań wytrzymałości na ścinanie, według normy ASTM A264

The static tensile test at room temperature was carried out in accordance with the PN-EN ISO 6892-1 standard [8]. The shearing tests were carried out in accordance with the guidelines of ASTM A264 [9], the sample production diagram is shown in Figure 1. Microstructural observations were carried out using an OLYMPUS DSX500 light microscope and an Inspect F scanning electron microscope at magnifications up to 10,000×. The microstructure was observed on samples taken from all clad plates in the state after intermediate annealing and after final heat treatment.

3. TEST RESULTS

3.1. PHYSICAL SIMULATIONS OF SEMI-INDUSTRIAL HOT ROLLING

Based on original experiments [5, 6, 11], the temperature of the beginning of hot rolling of the 42CrMo4/NANOS-BA® clad plates was determined for all variants of plastic processing, which was approximately 1100°C. The physical simulations were carried out on a reversible roller mill with a 550 mm diameter of smooth rollers. The measuring system of the rolling mill enables the measurement of power and energy parameters, such as the pressure force of the material on the rollers and the rolling moment.

Figures 2 and 3 show the course of the pressure forces observed during hot rolling of clad plates, according to variants 1 and 3, respectively, while Table 4 presents the force-energy parameters observed during all welding tests. The values of the material pressing forces on the rollers increase with the temperature decrease. The measurement results show that the values of the pressure force in the rolling process are on average from 520 kN to 850 kN.

3.2. BENDING STRENGTH

The samples taken from clad plates were bent to reach the angle of 180° and the bending strength was determined on the basis of the force observed during the tests. The deflection angle was measured after unloading. The bending tests for the two-layer samples were performed using

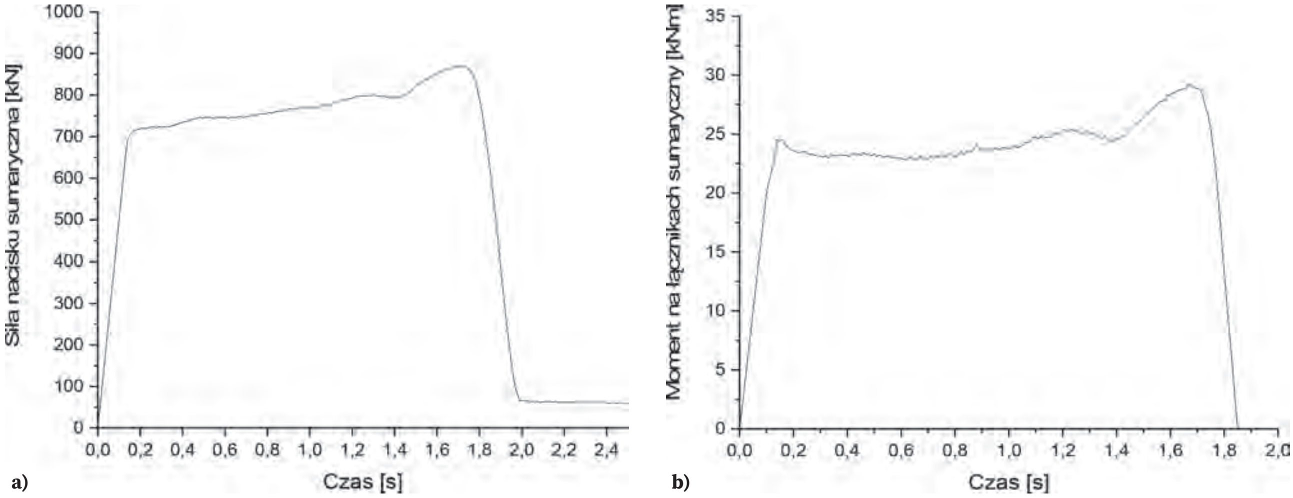


Fig. 2. Diagrams of a) material pressure forces on rollers and b) rolling moment for 42CrMo4/NANOS-BA® clad plates during one pass with a relative draft of 40% (option 1). Beginning of hot rolling at approximately 1100°C

Rys. 2. Wykresy przebiegów a) sił nacisku materiału na walce i b) momentu walcowania dla płaskowników platerowanych 42CrMo4/NANOS-BA® w trakcie jednego przepustu z gniotem względnym 40% (wariant 1). Początek walcowania na gorąco w temperaturze około 1100°C

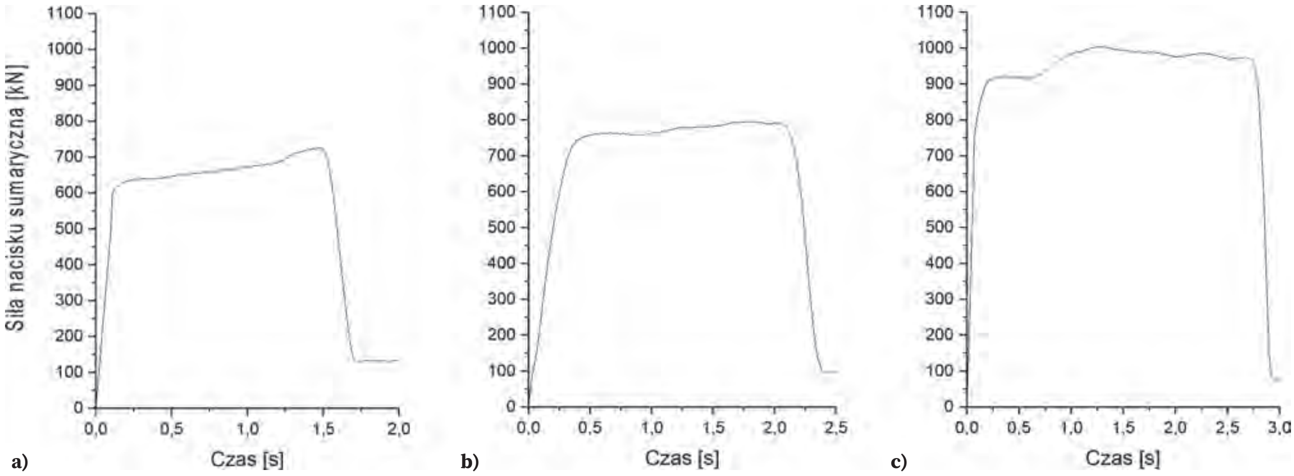


Fig. 3. Diagrams of the course of material pressure forces on the rollers for 42CrMo4/NANOS-BA® clad plates during the: a) first, b) second, and c) third pass, each time performed with a relative draft of 30% (option 3)

Rys. 3. Wykresy przebiegów sił nacisku materiału na walce dla płaskowników platerowanych 42CrMo4/NANOS-BA® w trakcie: a) pierwszego, b) drugiego i c) trzeciego przepustu, realizowanego każdorazowo z gniotem względnym 30% (wariant 3). Początek walcowania na gorąco w temperaturze około 1100°C

Table 4. Force-energy parameters observed during hot rolling tests of 42CrMo4/NANOS-BA® clad plates, according to three different variants

Tabela 4. Parametry siłowo-energetyczne zarejestrowane w trakcie prób walcowania na gorąco płaskowników dwuwarstwowych 42CrMo4/NANOS-BA®, według trzech różnych wariantów

No. samples ■ Oznaczenie próbek	No. pass ■ Nr przepustu	force on the drive side ■ Siła nacisku od strony napędu	Force on the operator's side ■ Siła nacisku od strony operatora	Total force ■ Siła nacisku całkowita	Moment on the top connector ■ Moment na łączniku górnym	Moment on the down connector ■ Moment na łączniku dolnym	Total moment of rolling ■ Moment całkowity
		[MN]	[MN]	[MN]	[kNm]	[kNm]	[kNm]
Variant 1 – in one pass, with a ~40% reduction ratio ■ Wariant 1 – jeden przepust z gniotem względnym ~40%							
S1	1	0.31	0.26	0.56	10.85	11.58	22.43
Variant 2 – in two passes, with a ~30% reduction ratio each ■ Wariant 2 – dwa przepusty, każdy z gniotem względnym ~30%							
S2	1	0.31	0.21	0.52	7.07	7.47	14.54
	2	0.36	0.28	0.63	18.51	20.52	39.00
Variant 3 – in three passes, with a ~30% reduction ratio each ■ Wariant 3 – trzy przepusty, każdy z gniotem względnym ~30%							
S3	1	0.29	0.23	0.52	6.34	7.38	13.72
	2	0.38	0.25	0.62	18.61	20.89	39.50
	3	0.48	0.37	0.85	25.53	28.62	54.15

Table 5. Results after bending test of samples taken from clad plates after additional isothermal annealing

Tabela 5. Wyniki prób zginania próbek pobranych z płaskowników platerowanych po dodatkowym wyżarzaniu izotermicznym

No. clad plate ■ Nr płaskownika	Basic layer/cladding layer ■ Warstwa podstawowa/ warstwa nakładana	Bending strength ■ Wytrzymałość na zginanie	Deflection angle ■ Kąt ugięcia	Results of bending tests to 180° angle ■ Wyniki próby zginania do kąta 180°
		R_g, [MPa]	[°]	
After one pass, with a ~40% reduction ratio and two stages heat treatment ■ Po jednym przepuście z gniotem względnym ~40% i dwuetapowej obróbce cieplnej				
S1	42CrMo4/NANOS-BA®	175	135	positive ■ pozytywny
	NANOS-BA®/42CrMo4	195	137	positive ■ pozytywny
After two passes, with a ~30% reduction ratio each and two stages heat treatment ■ Po dwóch przepustach, każdy z gniotem względnym ~30% i dwuetapowej obróbce cieplnej				
S2	42CrMo4/NANOS-BA®	301	164	positive ■ pozytywny
	NANOS-BA®/42CrMo4	113	49	negative/fracture ■ negatywny/pęknięcie
After three passes, with a ~30% reduction ratio and two stages heat treatment ■ Po trzech przepustach, każdy z gniotem względnym ~30% i dwuetapowej obróbce cieplnej				
S3	42CrMo4/NANOS-BA®	212	153	positive ■ pozytywny
	NANOS-BA®/42CrMo4	139	44	negative/fracture ■ negatywny/pęknięcie

a punch pressure from the side of the 42CrMo4 steel layer and the reverse side of the NANOS-BA® steel. The test results are shown in Table 5. For samples taken from clad plates No. S1, S2, and S3 after additional heat treatment, a deflection angle of 180° was obtained for all samples subjected to the bend test with a punch pressure from the side of the NANOS-BA® layer. The highest bending strength in this arrangement of layers, amounting to 301 MPa, was obtained for clad plate No. S2. In the case of the pressure of the punch from the 42CrMo4 layer side, the deflection angle of 180° was obtained only for sample S1. The bending strength in this configuration of the layer arrangement for this variant was 195 MPa. Sample photographs of samples after the tests are shown in Figure 4.

3.3. TENSILE STRENGTH

The mechanical properties of the experimental welds of 42CrMo4 and NANOS-BA® steels determined in the static tensile test are presented in Table 6. Sample photographs of samples after tensile tests are shown in Figure 5. On the basis of the obtained results, an upward trend in the values of mechanical properties $R_{p0.2}$, R_m and A was observed for 42CrMo4/NANOS-BA® clad plates along with an increase in the value of total draft during hot rolling with additional heat treatment. This is due to different diffusion mechanisms occurring during the joining of materials under the influence of pressure exerted on the surfaces, in each of the three different variants, and diffusion phenomena occurring in the joined surface during their heat treatment.

3.4. SHEAR STRENGTH

The list of the results of the shear strength tests is presented in Table 7, while the photographs of the samples after the test are shown in Figure 6. As a result of the performed tests, an increasing tendency of the shear strength of 42CrMo4/NANOS-BA® clad plates was observed, as a result of the use of increasingly higher total draft values during the welding of layers in the hot rolling process.

3.5. MICROSCOPIC TESTS

The structure was observed using an Olympus DSX500 light microscope and an Inspect F scanning electron microscope (SEM). No visible, distinct joined surface was found in the examined magnification range as a result of observations of the non-etched microsections from 42CrMo4/

Table 6. Results of mechanical properties, determined in a static tensile test of the obtained 42CrMo4/NANOS-BA® clad plates after final isothermal annealing

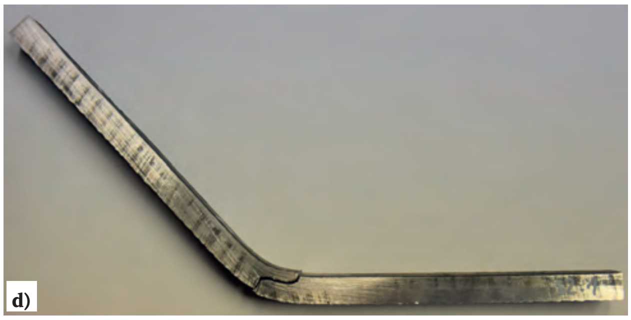
Tabela 6. Wyznaczone w statycznej próbie rozciągania właściwości mechaniczne płaskowników platerowanych 42CrMo4/NANOS-BA® po końcowym wyżarzaniu izotermicznym

No. ■ Lp.	Basic layer/cladding layer ■ Warstwa podstawowa/warstwa nakładana	$R_{p0,2}$, [MPa]	R_m, [MPa]	A, [%]
After one pass, with a ~40% reduction ratio and two stages heat treatment ■ Po jednym przepuście z gniotem względnym ~40% i dwuetapowej obróbce cieplnej				
1	42CrMo4/NANOS-BA® (S1)	935	1428	6.9
After two passes, with a ~30% reduction ratio each and two stages heat treatment ■ Po dwóch przepustach, każdy z gniotem względnym ~30% i dwuetapowej obróbce cieplnej				
2	42CrMo4/NANOS-BA® (S2)	983	1484	8.8
After three passes, with a ~30% reduction ratio and two stages heat treatment ■ Po trzech przepustach, każdy z gniotem względnym ~30% i dwuetapowej obróbce cieplnej				
3	42CrMo4/NANOS-BA® (S3)	1036	1504	10.9

Sample S1: 42CrMo4/NANOS-BA®

Sample S1: NANOS-BA®/ 42CrMo4

Sample S2: 42CrMo4/NANOS-BA®



Sample S2: NANOS-BA®/ 42CrMo4

Sample S3: 42CrMo4/NANOS-BA®

Sample S3: NANOS-BA®/ 42CrMo4

Fig. 4. Sample photographs after a two-sided bending test of samples taken from S1–S3 clad plates, arrangement of layers a), c), e) 42CrMo4/NANOS-BA®, b), d), f) NANOS-BA®/42CrMo4

Rys. 4. Przykładowe fotografie zginanych dwustronnie próbek pobranych z płaskowników platerowanych S1–S3, ułożenie warstw a), c), e) 42CrMo4/NANOS-BA®, b), d), f) NANOS-BA®/42CrMo4

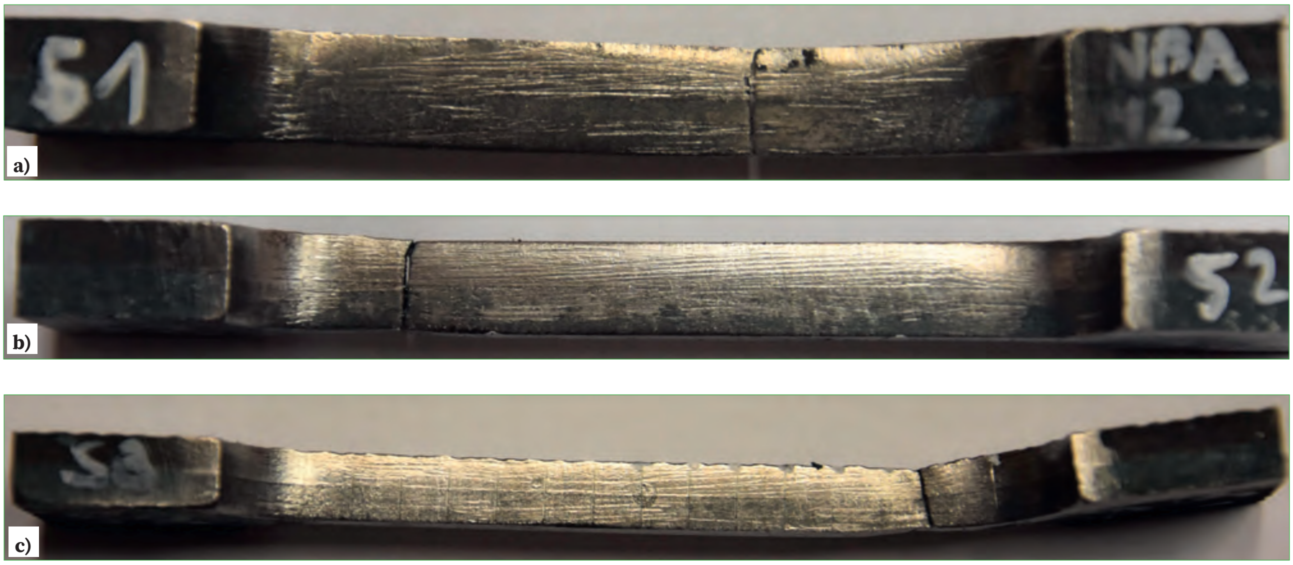


Fig. 5. Sample photographs of strength samples after tensile test at room temperature. The samples were taken from 42CrMo4/NANOS-BA® clad plates (basic layer – 42CrMo4; cladding layer – NANOS-BA®), after three different variants of hot rolling: one pass, with a ~40% reduction ratio (a), two passes, with a ~30% reduction ratio (b), three passes, with a ~30% reduction ratio (c) and two-stage heat treatment: 1) intermediate annealing and 2) isothermal annealing: 210°C /120 h

Rys. 5. Przykładowe fotografie próbek wytrzymałościowych po próbie rozciągania w temperaturze pokojowej. Próbki pobrano z płaskowników platerowanych 42CrMo4/NANOS-BA® (warstwa podstawowa – 42CrMo4; warstwa nakładana – NANOS-BA®), po trzech różnych wariantach walcowania na gorąco: jeden przepust z gniotem względnym ~40% (a), dwa przepusty, każdy z gniotem względnym ~30% (b), trzy przepusty, każdy z gniotem względnym ~30% (c) i dwuetapowej obróbce cieplnej: 1) wyżarzaniu międzyoperacyjnym i 2) wyżarzaniu izotermicznym: 210°C/120 h

a)

b)

c)

Fig. 6. Sample photographs of strength samples after shear test at room temperature. The samples were taken from 42CrMo4/NANOS-BA® clad plates, after three different variants of hot rolling: a) variant 1, b) variant 2, c) variant 3 and two-stage heat treatment: 1) intermediate annealing and 2) isothermal annealing: 210°C /120 h

Rys. 6. Przykładowe fotografie próbek wytrzymałościowych po próbie ścinania w temperaturze pokojowej. Próbki pobrano z płaskowników platerowanych 42CrMo4/NANOS-BA®, po trzech różnych wariantach walcowania na gorąco: a) wariant 1, b) wariant 2, c) wariant 3 i dwuetapowej obróbce cieplnej: wyżarzaniu międzyoperacyjnym i wyżarzaniu izotermicznym: 210°C/120

Table 7. Results of shear test, according to the ASTM A264 standard, of 42CrMo4/NANOS-BA® clad plates after additional isothermal annealing

Tabela 7. Wyniki próby ścinania, według normy ASTM A264, płaskowników platerowanych 42CrMo4/NANOS-BA® w stanie po dodatkowym wyżarzaniu izotermicznym

No. ■ Lp.	**Basic layer/ cladding layer ■ Warstwa podstawowa/warstwa nakładana**	**Shear strength ■ Wytrzymałość na ścinanie**
		R_t, [MPa]
After one pass, with a ~40% reduction ratio and two stages heat treatment ■ Po jednym przepuście z gniotem względnym ~40% i dwuetapowej obróbce cieplnej		
1	42CrMo4/NANOS-BA®	639
After two passes, with a ~30% reduction ratio each and two stages heat treatment ■ Po dwóch przepustach, każdy z gniotem względnym ~30% i dwuetapowej obróbce cieplnej		
2	42CrMo4/NANOS-BA®	625
After three passes, with a ~30% reduction ratio and two stages heat treatment ■ Po trzech przepustach, każdy z gniotem względnym ~30% i dwuetapowej obróbce cieplnej		
3	42CrMo4/NANOS-BA®	761

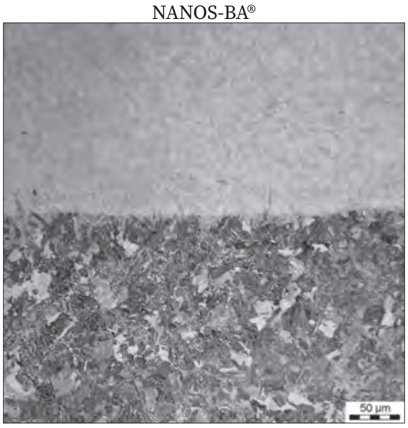
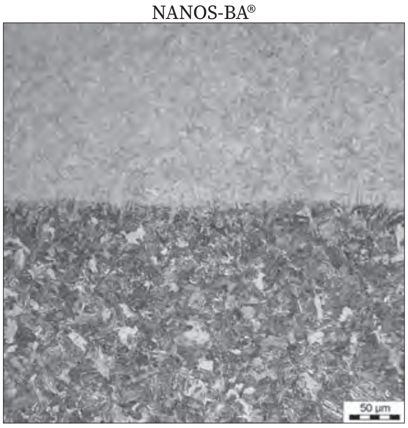
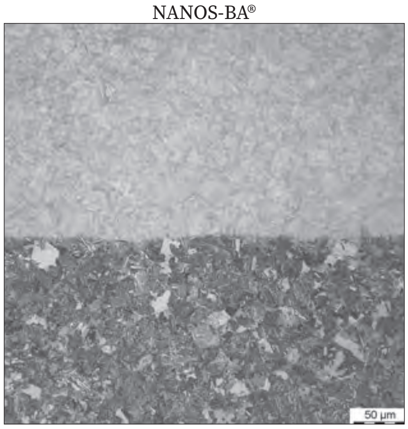
Table 8. Microphotography of clad plates within the joined surface. The samples were taken from 42CrMo4/NANOS-BA® clad plates after hot rolling, according to variants 1–3, and two-stage heat treatment, MS, longitudinal microsection, non-etched

Tabela 8. Mikrofotografia płaskowników platerowanych w obszarze linii zgrzewania. Próbki pobrano z płaskowników platerowanych 42CrMo4/NANOS-BA® w stanie po walcowaniu na gorąco, według wariantów 1–3 i dwuetapowej obróbce cieplnej, MS, zgład wzdłużny, nietrawiony

Variant 1 ■ Wariant 1	**Variant 2 ■ Wariant 2**	**Variant 3 ■ Wariant 3**
NANOS-BA®  42CrMo4	NANOS-BA®  42CrMo4	NANOS-BA®  42CrMo4
Plate No. S1 ■ Płaskownik nr S1	Plate No. S2 ■ Płaskownik nr S2	Plate No. S3 ■ Płaskownik nr S3

Table 9. Microstructure of clad plates within the joined surface. The samples were taken from 42CrMo4/NANOS-BA® clad plates after hot rolling, according to variants 1–3, and two-stage heat treatment, MS, longitudinal microsection, etched with Nital

Tabela 9. Mikrostruktura płaskowników platerowanych ze stali 42CrMo4/NANOS-BA® w obszarze linii zgrzewania. Próbki pobrano z płaskowników w stanie po walcowaniu na gorąco, według wariantów 1–3 i dwuetapowej obróbce cieplnej, MS, zgład wzdłużny, trawiony Nitalem

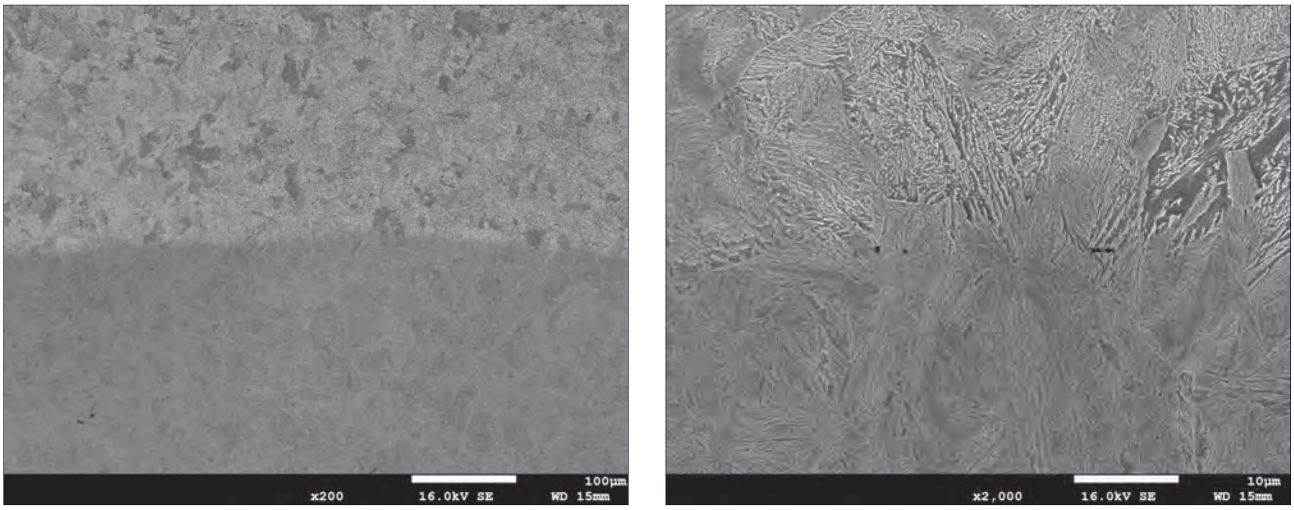
Variant 1 ■ Wariant 1	**Variant 2 ■ Wariant 2**	**Variant 3 ■ Wariant 3**
NANOS-BA®  42CrMo4	NANOS-BA®  42CrMo4	NANOS-BA®  42CrMo4
Plate No. S1 ■ Płaskownik nr S1	Plate No. S2 ■ Płaskownik nr S2	Plate No. S3 ■ Płaskownik nr S3

NANOS-BA® clad plates carried out using a light microscope. No cracks or other internal discontinuities were found in the area of the welding plane. This indicates the possibility of obtaining good-quality material combinations as a result of the rolling method used. Table 8 presents microphotographs taken in the welding area of the 42CrMo4 and NANOS-BA® steel layers after hot rolling and two-stage heat treatment. Table 9 presents photographs of samples taken from the same clad plates after etching with nital. Figures 7–9 show photographs of the microstructure of the S1, S2 and S3 clad plates in the welding area, taken with the use of a scanning electron microscope (SEM). The microstructure of NANOS-BA® steel is a two-phase structure, consisting of carbide-free lower bainite and residual austenite, characteristic for this steel grade after final isothermal annealing according to parameters 210°C/120 h. A multiphase microstructure was observed in the 42CrMo4 steel layer, consisting of a mixture of upper bainite and acicular ferrite, with a small proportion of pearlite.

4. SUMMARY

As a result of the technology proposed in the study for welding layers of non-weldable steel grades 42CrMo4 and NANOS-BA® in the hot rolling process, according to three different variants, clad plates obtained without macroscop-

42CrMo4 **42CrMo4**

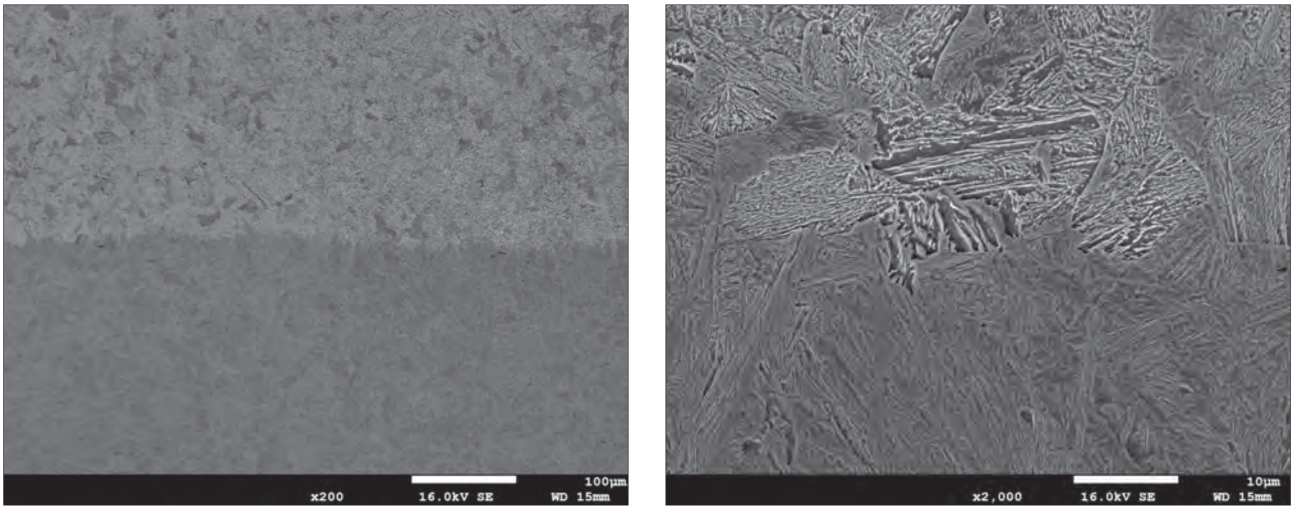


NANOS-BA® **NANOS-BA®**

Fig. 7. Microstructure of the 42CrMo4/NANOS-BA® clad plate No. S1, after hot rolling, in accordance with variant 1 and two-stage heat treatment. Joined surface, longitudinal microsection, SEM

Rys. 7 Mikrostruktura płaskownika platerowanego 42CrMo4/NANOS-BA® nr S1, w stanie po walcowaniu na gorąco, zgodnie z wariantem 1 i dwuetapowej obróbce cieplnej. Płaszczyzna zgrzewania, zgład wzdłużny, SEM

42CrMo4 **42CrMo4**

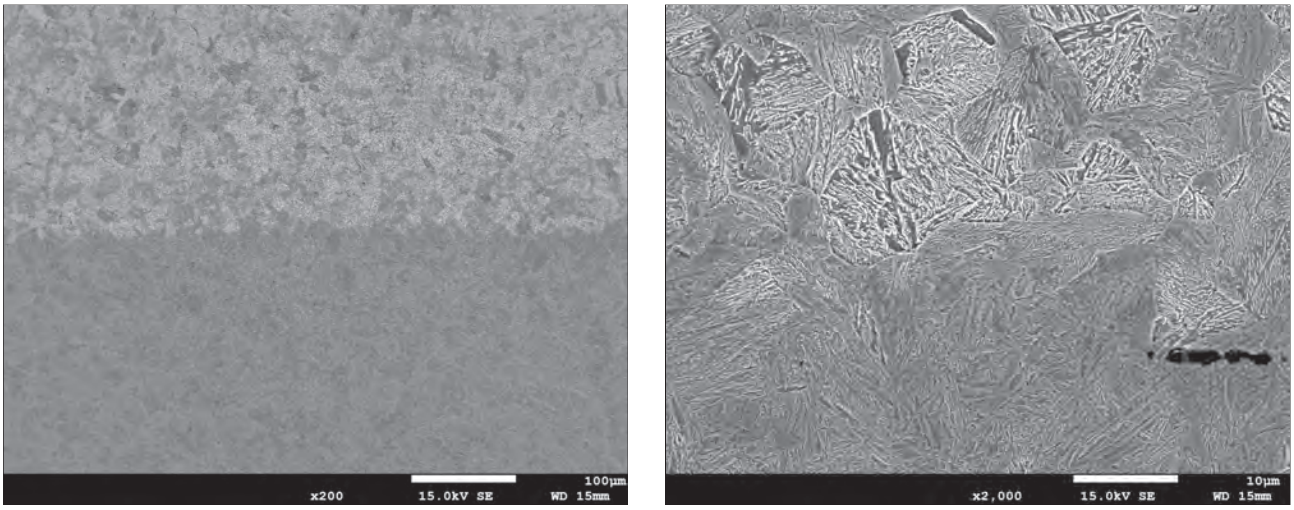


NANOS-BA® **NANOS-BA®**

Fig. 8. Microstructure of the 42CrMo4/NANOS-BA® clad plate No. S2, after hot rolling, in accordance with variant 1 and two-stage heat treatment. Joined surface, longitudinal microsection, SEM

Rys. 8. Mikrostruktura płaskownika platerowanego 42CrMo4/NANOS-BA® nr S2, w stanie po walcowaniu na gorąco, zgodnie z wariantem 1 i dwuetapowej obróbce cieplnej. Płaszczyzna zgrzewania, zgład wzdłużny, SEM

42CrMo4 **42CrMo4**



NANOS-BA® **NANOS-BA®**

Fig. 9. Microstructure of the 42CrMo4/NANOS-BA® clad plate No. S3, after hot rolling, in accordance with variant 1 and two-stage heat treatment. Joined surface, longitudinal microsection, SEM

Rys. 9. Mikrostruktura płaskownika platerowanego 42CrMo4/NANOS-BA® nr S3, w stanie po walcowaniu na gorąco, zgodnie z wariantem 1 i dwuetapowej obróbce cieplnej. Płaszczyzna zgrzewania, zgład wzdłużny, SEM

ically visible cracks and delamination, which proves that the process parameters were selected correctly. The results of laboratory tests carried out on samples taken from the 42CrMo4/NANOS-BA® clad plates prove that in the process of hot rolling and two-stage heat treatment, it is possible to obtain a permanent bond between the layers of 42CrMo4 and NANOS-BA® steels. The microscopic observations confirmed the high quality of welding of the produced clad plates was confirmed. By applying additional heat treatment with isothermal transformation of NANOS-BA® steel layers into nano-structured bainite, high mechanical properties were obtained for all macrocomposite clad plates made of 42CrMo4/NANOS-BA® steel.

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