Bartłomiej Walnik, Dariusz Woźniak, Mariusz Adamczyk,
Rafał Palus, Aleksandra Bagińska

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Study on the Microstructure and Technological Properties of Clad Plates Made of Steels S235jR and X20Cr13 and S235jR and X5CrNi18-10 after Hot Rolling

Badania mikrostruktury i właściwości technologicznych płaskowników S235JR/X20Cr13 i S235JR/X5CrNi18-10 po procesie walcowania na gorąco

Abstract: The article presents the results of physical experiments consisting in the rolling of layered plates (clad plates). The experiments involved two types of two-layered flat bars, i.e. S235JR and X20Cr13 as well as S235JR and X5CrNi18-10. The experiment resulted in the development of a technology for the fabrication of layered flat bars made of structural steel S235JR, corrosion-resistant steel X20Cr13 and austenitic acid-resistant steel X5CrNi18-10. Microstructural observations were performed using a light microscope (LM) and a scanning electron microscope (SEM). The observations revealed the possibility of obtaining permanent joints through hot rolling and the possibility of applying steel grades S235JR, X20Cr13 and X5CrNi18 in the fabrication of layered plates.

Key words: hot rolling, clad plates, carbon steel, alloy steel, hot rolling-bonding

Streszczenie: W artykule omówiono wyniki fizycznych eksperymentów walcowania blach warstwowych. Eksperymenty wykonano na dwóch rodzajach płaskowników dwuwarstwowych S235JR – X20Cr13 i S235JR – X5CrNi18-10. Wynikiem eksperymentów było opracowanie technologii wytwarzania płaskowników o budowie warstwowej, złożonych ze stali konstrukcyjnej S235JR oraz ze stali odpornej na korozję X20Cr13 i stali kwasoodpornej austenitycznej X5CrNi18-10. Badania mikrostruktury przeprowadzono przy użyciu techniki mikroskopii świetlnej i skaningowej mikroskopii elektronowej, SEM. Wyniki pracy wskazują, że dobrane parametry walcowania na gorąco pozwoliły na wytworzenie trwałego połączenia pomiędzy blachami w wyniku ich walcowania na gorąco i na możliwość zastosowania stali z gatunków S235JR, X20Cr13 i X5CrNi18 na blachy warstwowe.

Słowa kluczowe: walcowanie na gorąco, blachy warstwowe, stal węglowa, stal stopowa, zgrzewanie w procesie walcowania na gorąco

1. Introduction

Flat products composed of two or more permanently joined layers of different materials characterised by different physical properties are widely used in the electrical, machine-building, chemical, shipbuilding and automotive industries. Presently, flat steel layered products obtained through hot rolling are not manufactured in Poland. The technology of hot rolling of layered plates is applied by global producers such as ArcelorMittal or JFE Steel Corp. [1, 2]. The rolling of layered products is a technologically complicated process. The foregoing results from the varied properties of materials constituting component layers, deforming in various ways [3–5]. Presently, many research centres investigate hot rolling technologies enabling the obtainment of clad plates. Łukasiewicz – Upper-Silesian Institute of Technology performs research concerning the possibility of joining structural steel plates in the hot rolling process involving an approximate reduction of 40% in one pass [6] as well as research on the possibility of joining non-weldable steel grades NANOS-BA® and 42CrMo4 in the hot rolling process and two-stage heat treatment [7].

The current directions of research works are concerned with the possibility of developing technologies making it possible to join carbon steels with stainless steels in the hot rolling process with modified parameters [8]. Other research activities are focused on developing new methods enabling the fabrication of multilayer plates [9]. The research work discussed in the article involved the experimental hot rolling of two types of layered flat bars, i.e. S235JR+X20Cr13 and S235JR+X5CrNi18-10. The assessment concerning the stability of joints was based on material-related tests. Analyses also included the effect of flat bar surface preparation on the quality and stability of joints of plates obtained in the hot rolling process.

dr inż. Bartłomiej Walnik, dr hab. inż. Dariusz Woźniak, mgr inż. Mariusz Adamczyk, mgr inż. Aleksandra Bagińska – Łukasiewicz Research Network – Upper-Silesian Institute of Technology, mgr inż. Rafał Palus – Łukasiewicz Research Network –Institute of Non-Ferrous Metals

Corresponding author: bartlomiej.walnik@git.lukasiewicz.gov.pl

2. Test materials and methodology

Physical simulations concerned with the fabrication of layered products through hot rolling were performed at Łukasiewicz – Upper-Silesian Institute of Technology, using module B of the line for the semi-industrial simulation of product fabrication (LPS). The chemical compositions of the materials used in the tests are presented in Table 1. Designations, types of test steel grades and the specimen preparation method are presented in Table 2 and Figure 1. The experiments consisted in joining two layers of materials (having the same initial thickness) by high-temperature plastic deformation induced in the rolling process. The specimens were prepared as two sets of packages, numbered 1 and 2 and 3 and 4, having an initial thickness of 10 mm and that of 20 mm, respectively. The thickness variation was aimed at examining the effect of plastic processing on the stability of joints. In terms of packages nos. 1 and 3, the surfaces of the layers to be joined were additionally subjected to grinding. The grinding process was performed in order to examine the effect of layer surface quality on joint stability. All the test specimens were subjected to etching.

3. Test results

The physical simulation of the fabrication of layered products was performed using the semi-industrial line (LPS-B line) and the multi-pass reversing rolling method.

The tests involved the use of barrel-type rolls with a barrel diameter of 550 mm. The programme of the tests is presented in Tables 3 and 4. The specimens were heated up to a temperature of 1180 °C. The plastic processing temperature was restricted within the range of 1100 °C to 800 °C. The specimens were rolled to the same final thickness using a reduction of 30–45 %. After rolling, the specimens were cooled in still air.

The final dimensions and rolling process parameters are presented in Table 5. The degree of plastic processing was calculated as the quotient of cross-sections before and after rolling. Photographs of the rolled flat bars are presented in Figure 2.

The quality of the weld zone of the layers was examined using metallographic specimens cut out transversely to the rolling direction. Metallographic examinations involved unetched specimens and specimens etched in a few percent solution of nitric acid in ethanol (Nital). Microscopic observations were performed using an optical-digital microscope and magnification restricted within the range of 100× to 2000× as well as a scanning electron microscope and magnification restricted within the range of 100× to 10000×. The SEM-based tests involved the use of a detector enabling the analysis of the chemical composition of the material in micro-areas. An exemplary macrostructure is presented in Figure 3.

The observations revealed that all the flat bars were characterised by a compact internal structure within the entire cross-section. Macroscopic observations did not reveal any delamination or local discontinuities along the weld plane.

Table 1. Chemical compositions of test steel grades, [wt%]

No.	Steel grade	C	Mn	Si	P	S	Cr	Ni	Mo	V	Ti	Al_{calk}	Cu
1	S235JR	0.074	1.49	0.020	0.014	0.005	0.020	0.018	<0.005	<0.003	0.0021	0.040	0.013
2	X20Cr13	0.15	0.44	0.24	0.022	<0.010	13.17	0.24	-	-	-	-	0.04
3	X5CrNi18-10	0.026	1.96	0.44	0.039	0.003	17.76	9.73	0.57	-	0.07	-	0.46

Table 2. Dimensions of two-layered flat bars used in hot roll bonding tests with the semi-industrial simulation line (LPS)

Designation of specimen/ package	Steel grades		Pre-weld contact surface preparation	Specimen dimensions, [mm]
	Material 1	Material 2		
1	Stal S235JR	Stal X20Cr13	grinding + etching	10.0 × 80 × 195
2	Stal S235JR	Stal X20Cr13	etching	10.5 × 80 × 195
3	Stal S235JR	X5CrNi18-10	grinding + etching	20.3 × 36 × 200
4	Stal S235JR	X5CrNi18-10	etching	20.7 × 36 × 200

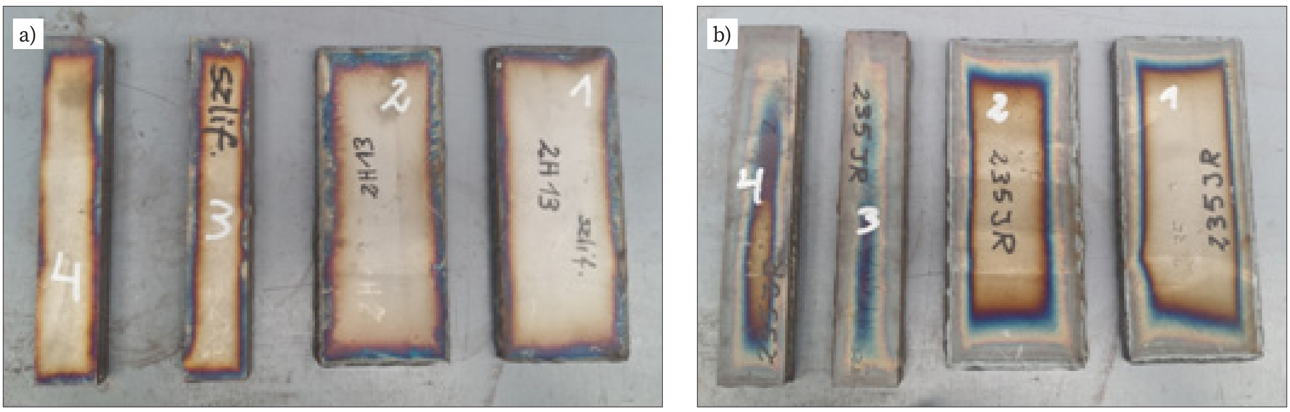


Fig. 1. Photographs of the layered specimens before hot rolling in LPS/B: alloy steel surface (a) and low-carbon steel surface (b)

Table 3. Parameters assumed for the rolling of specimens 1 and 2 (S235JR + X20Cr13); specimen dimensions: 10 mm × 80 mm ×195 mm

Heating					
Temperature, 1180 °C			Time, 10 min		
Pass	**Roll gap setting [mm]**	**Relative reduction [%]**	**Actual reduction**	**Rolling rate [m/s]**	**Strip temperature, [°C]**
Charge	10				
1	5.5	45	0.60	0.10	1100
2	3.5	36	0.45	0.20	-
3	2.3	34	0.42	0.30	-
4	1.5	35	0.43	0.40	-
5	1.0	33	0.41	0.50	800
1-5	Total actual reduction		2.31	-	-
Cooling conditions			**Approximate temperature range, [°C]**		
Air			800-RT		

Table 4. Parameters assumed for the rolling of specimens 3 and 4 (S235JR + X5CrNi18-10); specimen dimensions: 20 mm × 36 mm ×200 mm

Heating					
Temperature, 1180 °C			Time, 20 min		
Pass	**Roll gap setting [mm]**	**Relative reduction, [%]**	**Actual reduction**	**Rolling rate [m/s]**	**Strip temperature [°C]**
charge	20				
1	12.2	39	0.49	0.10	1100
2	7.3	40	0.51	0.20	-
3	4.3	41	0.53	0.30	-
4	2.6	40	0.50	0.40	-
5	1.6	39	0.49	0.50	-
6	1.0	38	0.47	0.50	800
1-6	Total actual reduction		2.50	-	-
Cooling conditions			**Approximate temperature range, °C**		
Air			800-RT		

Table 5. Averaged dimensions and parameters used in the rolling of layered flat bars in line LPS/B

No.	Specimen designation	Thickness [mm]	Width [mm]	Length [mm]	Total actual reduction	Plastic processing degree
1	1	2.69	152	760	1.31	2.0
2	2	2.68	152	780	1.37	2.1
3	3	2.48	64	990	2.10	4.6
4	4	2.70	64	1015	2.04	4.3

Fig. 2. Photographs of layered flat bars after hot rolling in the semi-industrial simulation line (module B-LPS)

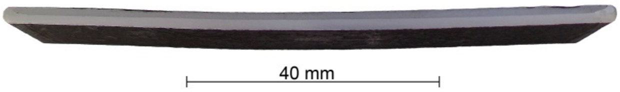


Fig. 3. Macrostructure of layers of steel S235JR and X20Cr13 joined through rolling, visible in the cross-section of specimen 1

In the cross-section, it was possible to notice varied thicknesses of individual layers. In the cross-section of specimen 1, the thickness of layers amounted to ~1.1 mm (steel S235JR) and ~1.6 mm (steel X20Cr13). The difference in thickness resulted from the varied plastic deformability of materials having various chemical compositions. The greatest deformation was observed in terms of the material layer made of low-alloy steel.

The results of the microscopic tests concerning the weld plane of the layers are presented in Figures 4–8. The tests of the unetched specimens revealed the noticeable effect of the pre-roll layer contact surface preparation on the quality of material in the weld zone. It was possible to observe that the areas of joints contained non-metallic inclusions.

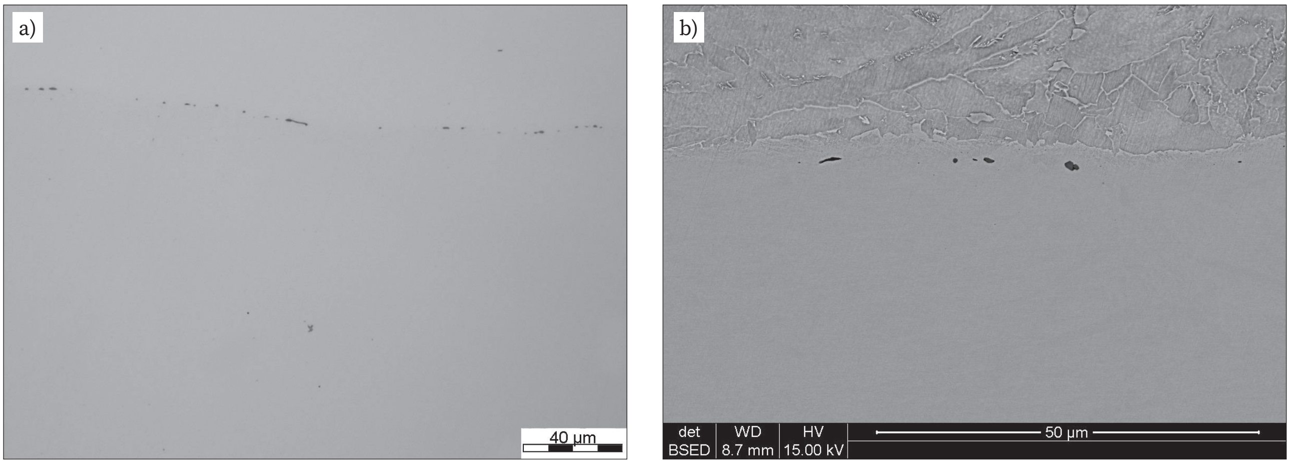


Fig. 4. Microstructure of the layered plate made of steel S235JR and steel X20Cr13 (variant 2): a) unetched specimen (LM) and b) specimen etched with Nital (SEM)

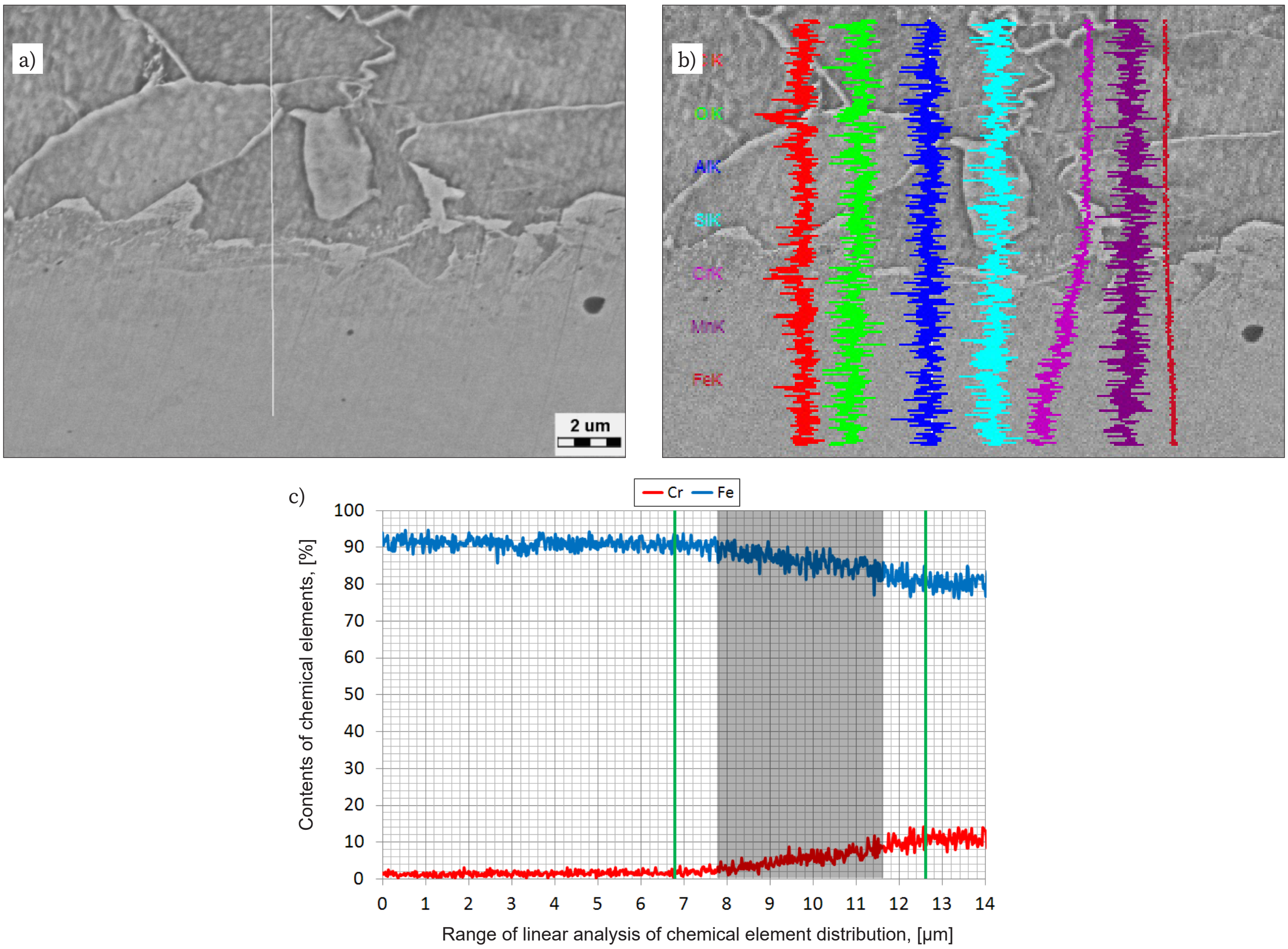


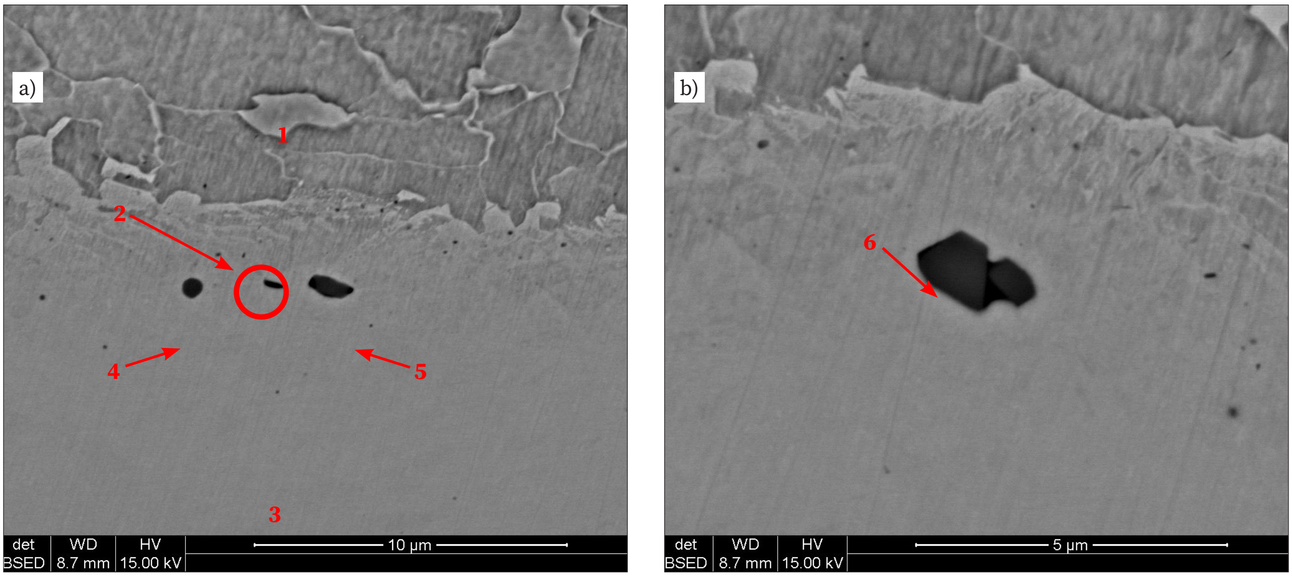
Fig. 5. Linear analysis of the distribution of chemical elements in the cross-section of the weld zone of steel S235JR with steel X20Cr13 (SEM): a) area of analysis along with the measurement line, b) curves of distributions of selected chemical elements and c) change in contents of Cr and Fe (%)

In terms of the flat bars, where the surfaces of plates to be joined were not subjected to grinding before etching, it was possible to observe that the weld zone was characterised by a greater number of clusters of non-metallic inclusions. It was possible to observe the presence of surface oxidation products originating from the fabrication of component layers. The microanalysis of the chemical composition of the inclusions revealed the presence of complex oxides of iron, manganese, silicon, aluminium and chromium. The above-named areas also contained small single MnS-type sulphide inclusions. The microscopic examinations did not reveal the presence of any internal discontinuities of the material in the weld area.

The microscopic observations of the joint area did not reveal any clear separation plane between the joined layers of unalloyed steel S235JR and high-alloy steels X20Cr13 and X5CrNi18-10. At high magnification, it was possible to observe the presence of a transition zone between the layers, manifested by a gradual loss of details in the morphology of the structure of steel S235JR. The results of the observations were confirmed in the SEM-based tests, performed using the linear analysis of the distribution of elements in the cross-section of the weld zone (Fig. 5) and the analysis of the chemical composition of steel in micro-areas (Fig. 6 and 8).

The results revealed that the cross-section of the joint was characterised by gradual changes in the contents of iron and alloying elements. The foregoing indicated the obtainment of the permanent diffusion joint of the surfaces of the layers. The formation of the joints resulted from the effect of high temperature and pressure triggered by plastic strain. The thickness of the transition zone, assessed using quantitative metallography amounted approximately 5 mm as regards the joint of steel S235JR and X20Cr13 and approximately 10 mm in terms of the joints of steel S235JR and X5CrNi18-10.

The investigation concerned with the adhesion of hot roll-bonded layers involved the performance of static tensile tests. The tensile tests involved flat bars nos. 1 and 2, made of steel S235JR and X20Cr13. The specimens were rolled using parameters creating less favourable conditions for ob-



Area 1		
Element	**wt %**	**at %**
Al	0.2	0.4
Si	0.2	0.3
Cr	0.5	0.6
Mn	1.1	1.1
Fe	98.1	97.7

Area 2		
Element	**wt %**	**at %**
Al	0.2	0.4
Si	0.2	0.3
Cr	4.3	4.5
Mn	0.8	0.8
Fe	94.6	94

Area 3		
Element	**wt %**	**at %**
Si	0.4	0.7
Cr	12.3	13
Mn	0.4	0.4
Fe	87	85.9

Area 4		
Element	**wt %**	**at %**
O	16.6	40.3
Al	0.4	0.6
S	0.3	0.3
V	0.4	0.3
Cr	22.1	16.5
Mn	7.8	5.5
Fe	52.3	36,4

Area 5		
Element	**wt %**	**at %**
O	23	49.6
Al	0.5	0.7
Si	1.5	1.9
S	0.3	0.4
Ca	0.4	0.3
Cr	27.2	18.1
Mn	12,8	8
Fe	34,2	21,1

Area 6		
Element	**wt %**	**at %**
O	25.8	53.6
Al	0.5	0.6
Si	0.1	0.2
V	0.7	0.5
Cr	35.5	22.7
Mn	12.3	7.5
Fe	25	14,9

Fig. 6. Microanalysis of the chemical composition of the material in the joint of steel S235JR with steel X20Cr13 (variant 2) as well as of the chemical composition of non-metallic inclusions (SEM)

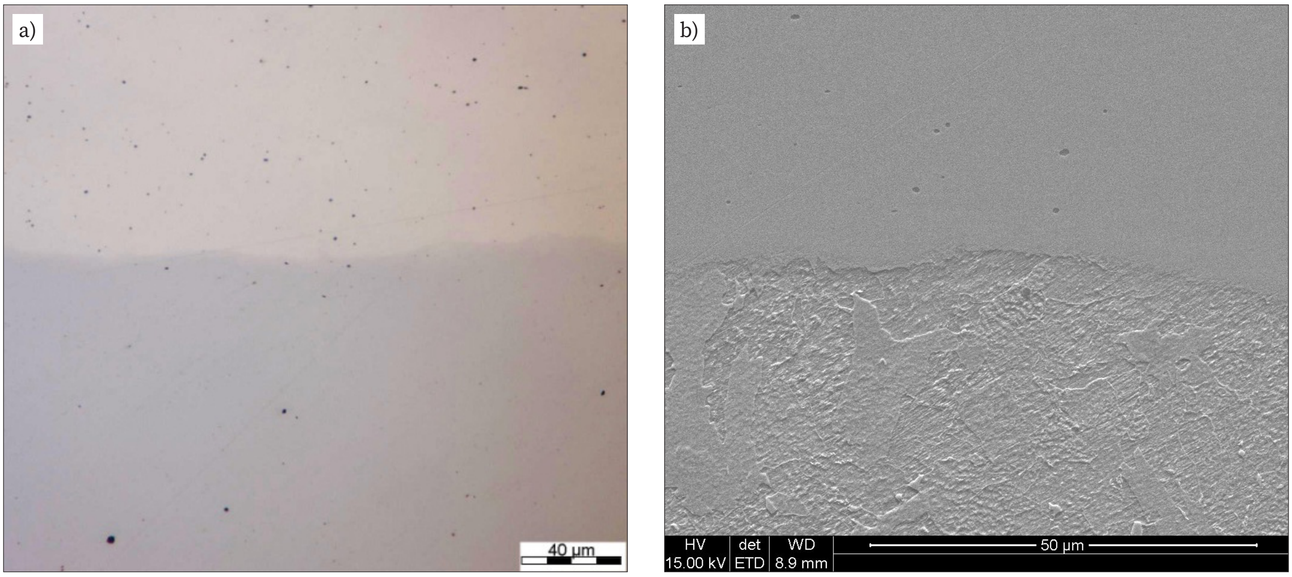
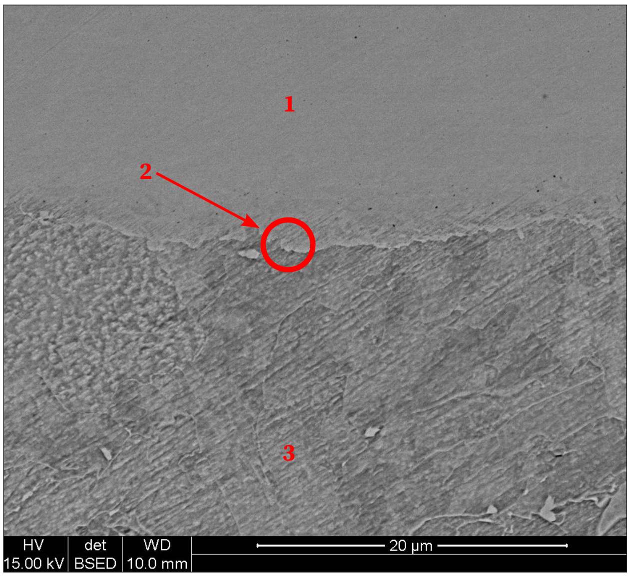


Fig. 7. Microstructure in the longitudinal section of specimen 3 after hot rolling – joint of steel S235JR with steel X5CrNi18-10 (variant 3): a) unetched specimen (LM) and b) specimen etched with Nital, (SEM)

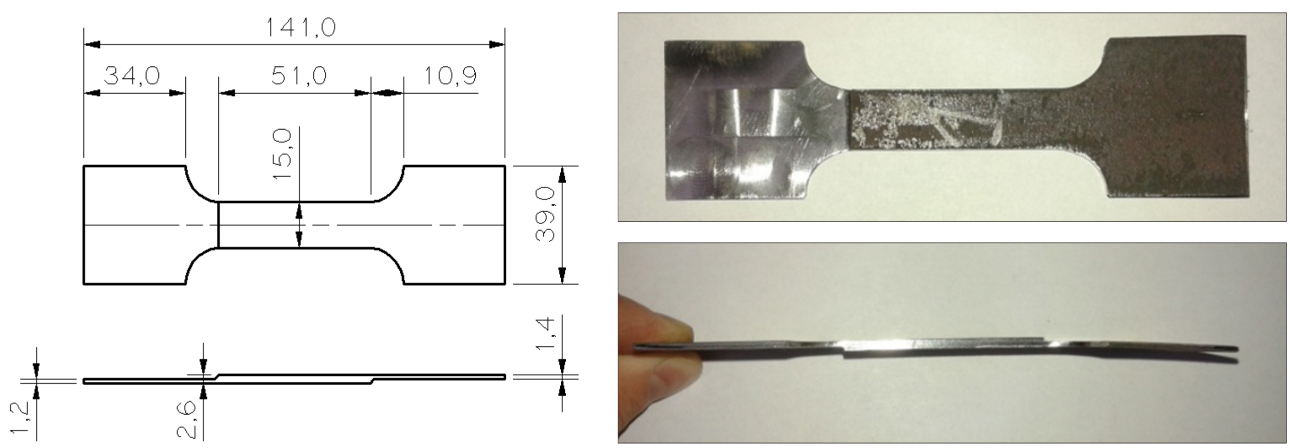


Area 1		
Element	**wt %**	**at %**
Si	0.7	1.3
Cr	17.8	18.8
Mn	1.1	1.1
Fe	73.0	71.8
Ni	7.5	7.0

Area 2		
Element	**wt %**	**at %**
Si	0.2	0.4
Cr	4.9	5.2
Mn	1.1	1.1
Fe	92.8	92.3
Ni	1.1	1.0

Area 3		
Element	**wt %**	**at %**
Si	0.1	0.1
Mn	1.0	1.0
Fe	98.9	98.8

Fig. 8. Microanalysis of the chemical composition of material in the joint of steel S235JR with steel X5CrNi18-10 (variant 3), SEM



ig. 9. Dimensions of the specimens used in the static tensile tests performed using a Z250 testing machine (ZwickRoell)

Table 6. Static tensile test results concerning the transverse specimens sampled from the layered flat bars

Specimen designation	Specimen dimensions		$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]	Rupture force [kN]
	Cross-section of the parallel part [mm]	Gauge length L_0 [mm]				
1a	2.70 × 15	50.0	570	1151	4.6	46.6
2a	2.67 × 15	50.0	622	1089	2.9	43.6

taining the permanent joint of the layers, i.e. characterised by a lower value of total reduction. The tests involved the specimens positioned transversely to the rolling direction. The dimensions of the specimens designated as 1a and 2a and photographs of the specimens after the tensile tests are presented in Figure 9.

The milling method was used to remove the individual layers of welded materials so that only the parallel part would include the total thickness of the rolled flat bar. The tensile force triggered the generation of shear stresses in the weld plane, favouring the loss of material adhesion and the delamination of joined layers.

The tensile test results revealed that the rolled layered flat bars (S235JR + X20Cr13) were simultaneously characterised by high tensile strength and low plasticity. The above-named properties resulted primarily from the structure of the thicker layer of steel X20Cr13 after cooling in the air. It could be expected that greater elongation would be obtained in relation to the specimens subjected to tempering. Both layered specimens, i.e. 1a and 2a, were characterised by favourable joint stability. It was also revealed that the pre-roll layer surface preparation (grinding or the lack of grinding) did not affect the test result. The test results concerning the mechanical properties of the specimens are presented in Table 6.

4. Conclusions

The above-presented test results related to the physical simulation of the hot-rolling-based fabrication of layered steel products led to the formulation of the conclusions presented below.

1. The experimental rolling of layered flat bars composed of steel S235JR+X20Cr13 and steel S235JR+X5CrNi18-10 led to the obtainment of the stable joints of the test materials, resulting from the diffusion welding of the test plate surfaces. The joint was formed as a result of high-temperature effect, accelerating the diffusion and interatomic interactions of the materials in the area of joined surfaces as well as pressure exerted on these surfaces and triggered by plastic strain.
2. The obtainment of the permanent joint of layered flat bars through hot rolling required the appropriate preparation of the contact surfaces of the plates and the elimination of the oxidability of these surfaces during heating preceding the rolling process. It was necessary to remove impurities and oxide layers (remaining after the manufacturing process) from the plate surface. The surfaces of materials should be characterised by flatness, ensuring the proper adhesion of the plates in the entire area of contact.
3. After rolling, the flat bars prepared in the above-named manner did not undergo material delamination.
4. The performance of the physical simulations enabled the determination of the preliminary technological parameters used in the hot rolling of layered steel products, enabling the obtainment of permanent joints of steel grades characterised by varied chemical compositions. The obtainment of the aforesaid joints necessitated the rolling of appropriately prepared packages within the temperature range of 1100 °C to 800 °C and the use of several passes, characterised by a total relative reduction of approximately 70 %.

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