Michał Szymura, Artur Czupryński

The Effect of a Welding Technology on the Abrasive Wear Resistance of Joints in Abrasion-Resistant Plates

Abstract: The article presents results of tests concerning the metal-mineral abrasive wear resistance of butt welded joints with abrasion-resistance overlay weld HARDPLATE 100S 5+3 made using a covered electrode with the solid core and the flux core as well as a self-shielded flux-cored wire. The significance of the above-named effect was determined using a completely randomized design. The scope of tests also included the analysis of the chemical and phase compositions, hardness measurements as well as the macro and microscopic metallographic tests of welded joints in abrasion-resistant plates.

Keywords: welding, abrasion-resistant plates, covered electrode, tubular electrodes, flux-cored electrodes

DOI: *10.17729/ebis.2020.5/6*

Introduction

The most typical type of wear affecting elements of machinery and industrial equipment is abrasive wear (abrasion). It is estimated that abrasive wear may be responsible for more than 60% of costs resulting from tribological wear. Machinery elements made of plates provided with an abrasion-resistant overlay weld (abrasion-resistant plates) may be severalfold more resistant to abrasive wear than many abrasion-resistant steel grades [1, 2].

The widespread use of abrasion-resistant plates also results from the fact that they can be fixed using permanent (e.g. welded) joints (Fig. 1) and separable (e.g. bolted) joints as well as can be shaped using plastic working (rolling, bending) and machining (e.g. grinding). Usually, the welding of elements made of abrasion-resistant plates involves the use of filler metals recommended by the manufacturer of plates. In industrial practice, the abrasion-resistant layers of arc surfaced plates are joined using self-shielded flux-cored wires as well as covered electrodes with solid or flux cores [1, 3–5].

The abrasion resistance of surfaced layers depends primarily on a surfacing technology, connected with the type of a filler metal. Various properties of overlay welds made using various filler metals having the same chemical composition of weld deposit may result from differences related to dilution with the base material, cooling rates and metallurgical reactions occurring during the process [6–8].

Available reference publications present results of tests concerning the abrasive wear resistance of overlay welds of selected abrasion-resistant plates and joints of such plates made using one type of a covered electrode

mgr inż. Michał Szymura (MSc Eng.), dr inż. Artur Czupryński (PhD (DSc) Eng.) – Silesian University of Technology; Department of Welding Engineering

[3, 4, 9]. However, it was not possible to find quantitative data enabling the comparison of the functional properties of welded joints with the abrasion-resistant overlay weld made using various technologies. The lack of the above-named data inspired tests aimed to determine how a given technology applied for the welding of abrasion-resistant plates affects the abrasion resistance of joints.

The article presents results of tests concerning the metal-mineral abrasive wear resistance of butt welded joints with abrasion-resistance overlay weld HARDPLATE 100S 5+3 made using a covered electrode with the solid core and the flux core as well as a self-shielded flux-cored wire. The significance of the above-named effect was determined using a completely randomized design. The scope of tests also included the analysis of the chemical and phase compositions, hardness measurements as well as the macro and microscopic metallographic tests of welded joints in abrasion-resistant plates.

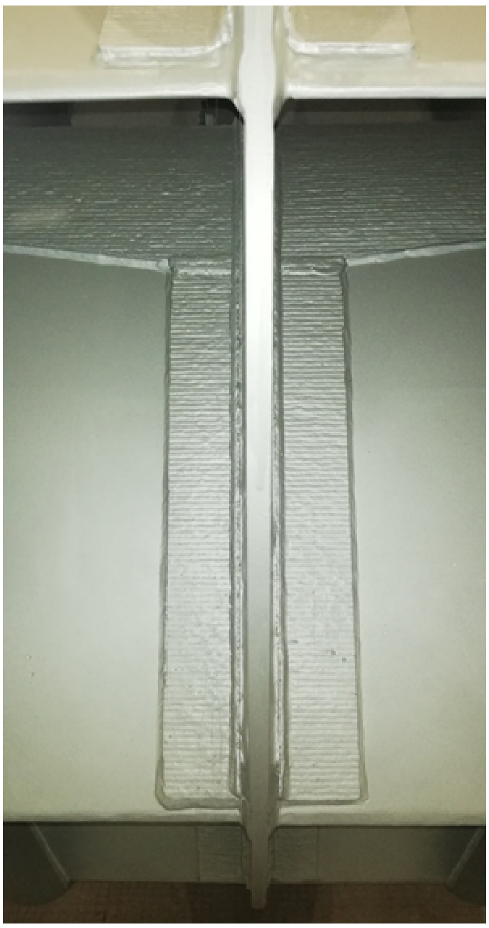


Fig. 1. Fan rotor with blade shields made of abrasion--resistant plates

Test materials

HARDPLATE 100S 5+3 abrasion-resistant plates are made in the process of automatic self-shielded flux-cored surfacing providing the obtainment of high-alloy chromium cast iron Fe15 (in accordance with PN-EN 14700:2014-06). The process involves the making of approximately 3.0 mm thick string runs on the substrate of 5.0 mm thick unalloyed steel S235JR (in accordance with PN-EN 10025-2:2019-11). The plates are used to protect surfaces exposed to intense metal-mineral abrasive wear and moderate impact loads.

Following the manufacturer's recommendations, the layers of abrasion-resistant plates were joined using covered electrodes with the solid core (Hardface HC-E), tubular electrodes (Hardface HC-TE) and self-shielded flux-cored wires (Hardface HC-O). The chemical composition of the weld deposit of the filler metals and the values of hardness after surfacing are presented in Table 1 [5]. The substrate of the plates with the abrasion-resistant overlay weld was joined using covered electrodes having a diameter of 3.2 mm (classification of E 42 4 B 4 2 H5 in accordance with PN-EN ISO 2560:2010) and a metallic flux-cored wire having a diameter of 1.2 mm (classification T 46 6 M M 1 H5 in accordance with PN-EN ISO 17632:2016-02).

Tests

Abrasive wear resistance tests

The tests aimed to identify the significance of a technology applied for the welding of the HARDPLATE 100S abrasion-resistant plates on the abrasive wear resistance of butt joints were performed using a completely randomised design making it possible to determine the significance of one input factor on an output factor [10]. The adopted effect significance level was $\alpha = 0.05$. It was assumed that the test joints would be made using three various arc welding technologies and that 6 tests of metal-mineral

Table 1. Diameter, the chemical composition of the weld deposit of the filler metals and hardness after surfacing [5]

Filler metal (trade name)	Diameter, mm	Chemical composition of weld deposit, % by weight					Hardness of the third layer of the overlay weld, HRC
		Fe	C	Cr	Si	Mn	
Covered electrode with the solid core (Hardface HC-E)	3.2	rest	5.0	35.0	1.0	0.5	60–63
Flux-cored covered electrode (Hardface HC-TE)	6.0	rest	5.8	30.0	0.8	0.9	61
Self-shielded flux-cored wire (Hardface HC-O)	1.6	rest	5.0	27.0	1.5	1.5	58–64

abrasive wear resistance would be performed in relation to each variant of the joint. Following the previously adopted assumptions and the concept of randomisation, 36 HARDPLATE 100S 5+3 plates were designated with natural subsequent numerals from 1 to 36 (based on the date of manufacture, from the oldest to the latest). An analogous approach was adopted in relation to the filler metals used to join the layers of the surfaced plates; the filler metals were designated as 18 batches. Afterwards, a computed generator of random numbers was used to obtain two sequences of random numbers [11]. The generated sequences of numbers were used to randomly assign the abrasion-resistant plates to the batches of the filler metal. The schedule of measurements of the completely randomised design taking into account the previously specified assumptions and plate-filler metal assignments are presented in Table 2 [10]. The plates were sampled for specimens having dimensions of 350 mm x 150 mm and arranged so that the longer side of the specimen was parallel to the welding sequence direction

Table 2. Schedule of completely randomised design measurements

Joint designation	Abrasion-resistant plates used for the making of the joint (designation of the first plate; designation of the second plate)	Filler metal designation	Trade name of the filler metal
A1	4; 25	16	Hardface HC-E
A2	10; 7	7	Hardface HC-E
A3	34; 15	11	Hardface HC-E
A4	35; 16	8	Hardface HC-E
A5	6; 30	15	Hardface HC-E
A6	8; 24	12	Hardface HC-E
B1	21; 2	2	Hardface HC-TE
B2	13; 28	9	Hardface HC-TE
B3	31; 26	4	Hardface HC-TE
B4	1; 36	1	Hardface HC-TE
B5	9; 20	6	Hardface HC-TE
B6	32; 33	17	Hardface HC-TE
C1	14; 5	14	Hardface HC-O
C2	17; 3	18	Hardface HC-O
C3	18; 12	10	Hardface HC-O
C4	27; 22	13	Hardface HC-O
C5	29; 19	5	Hardface HC-O
C6	23; 11	3	Hardface HC-O

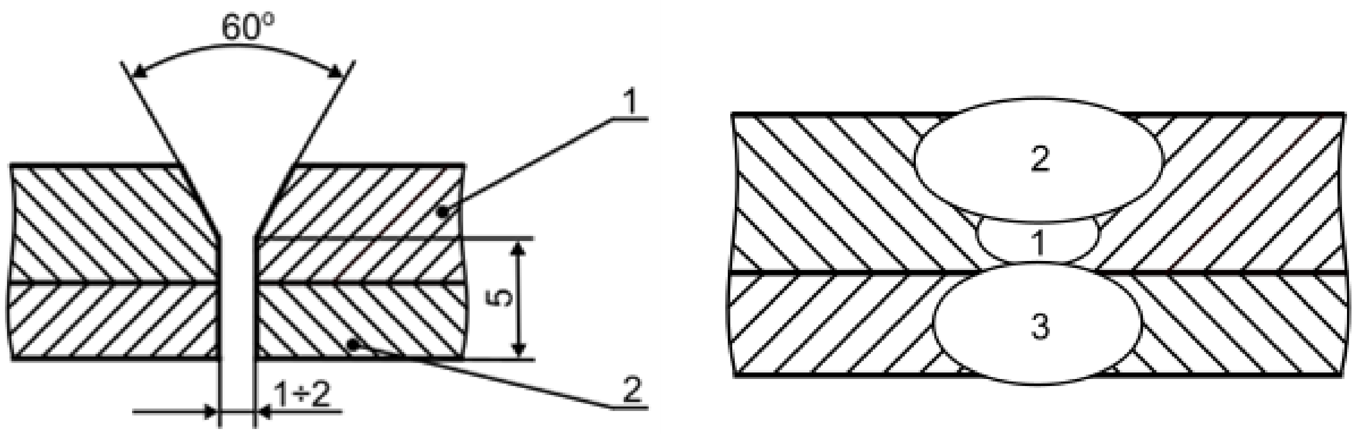


Fig. 2. Schematic diagram of: a) pre-weld joint preparation (1 – substrate material, 2 – surfaced layer); b) welding sequence

(i.e. the direction of the deposition of overlay welds). The preparation of the plates is presented in Figure 2a. The welding sequence is presented in Figure 2b. Before the deposition of subsequent runs, the penetration run was subjected to grinding on both sides. The technological parameters used during the making of the joints are presented in Table 3. Afterwards, each joint was sampled for a specimen having dimensions of 75 mm x 25 mm. The specimens were cut out so that their longer side was parallel to the side of the 350 mm long plate and that the symmetry axis of the pass of a single specimen overlapped with the weld axis. The location of cracks in the abrasion-resistant layer was accidental. The cut-out specimens were subjected to girth abrasive grinding.

The tests concerning the metal-mineral abrasive wear resistance of the joints made in the abrasion-resistant plates were based on the ASTM G 65 standard, procedure A. During the tests, the abrasive flow rate amounted to 309 g/min. The constant force of loads affecting the specimens amounted to 130 N. The abrasive wheel rotated at a rate of 200 rpm, whereas the abrasion distance amounted to 4309 m. The

Table 3. Parameters used in the welding of the joints in the abrasion-resistant plates

Designation of joints	Run no.	Welding process	Classification / filler metal trade name	Filler metal wire diameter, mm	Welding current, A	Arc voltage, V	Filler metal wire feeding rate, m/min	Welding rate, cm/min	Heat input*, kJ/mm
A1–A6	1	111	E 42 4 B 4 2 H5**	3.2	123	25.2	-	20.1	0.74
	2	111	E 42 4 B 4 2 H5**	3.2	137	25.3	-	14.6	1.14
	3	111	Hardface HC-E	3.2	139	27.2	-	16.7	1.09
B1–B6	1	111	E 42 4 B 4 2 H5**	3.2	127	25.2	-	20.4	0.75
	2	111	E 42 4 B 4 2 H5**	3.2	138	25.3	-	14.3	1.17
	3	111	Hardface HC-TE	6.0	132	25.9	-	17.6	0.93
C1–C6	1	138	T 46 6 M M 1 H5***	1.2	142	20.5	4.9	27.9	0.50
	2	138	T 46 6 M M 1 H5***	1.2	209	21	5.6	27.5	0.76
	3	114	Hardface HC-O	1.6	267	26.6	5.7	43.2	0.79

* heat input calculated in accordance with PN-EN 1011-1:2009, for k = 0.8;
** classification in accordance with PN-EN ISO 2560:2010;
*** classification in accordance with PN-EN ISO 17632:2016-02.

abrasive material was flame-dried quartz sand having spherical grains and granularity restricted within the range of 100 μm to 300 μm. The determination of the abrasive wear resistance of the joints required the performance of mass decrement measurements as well as the measurements of abrasion-resistant layer density. Before and after the tests the specimens were weighed using a laboratory balance; the measurement accuracy was up to 0.0001 g. The mean density of the abrasion-resistant layer was determined using the laboratory balance. The density test was based on three measurements concerning one specimen of each variant of the joint. The specimens were weighed in air and liquid. The decrement of volume was determined in accordance with formula (1), using the value of the mass decrement of the specimen and the mean value of the density of the abrasion-resistant layer (1). The results are presented in Table 4.

$$U_o = \frac{U_m}{\rho} \cdot 1000$$

where
Uo – volume decrement, mm³;
Um – mass decrement, g;
ρ – density, g/cm³.

The Table of the analysis of variance (Table 5) was made in accordance with the completely randomised design. The comparison concerning the abrasive wear resistance of the joints involved additional tests of six specimens sampled from the Hardplate 100S 5+3 plates (Table 6).

Hardness measurements

Measurements of the hardness of the abrasion resistant layer of the joints and the Hardplate 100S plates not subjected to welding was performed using the Rockwell method in accordance with the PN-EN ISO 6508-1:2016-10 standard. In relation to each specimen, five measurements were performed on the previously ground surface of the face of the abrasion-resistant layer (Fig. 3a). The Vickers hardness tests involved one specimen selected from each variant of the joint, i.e. the surface of the cross-section in the penetration area of the run joining the surfaced layer, the heat affected zone (HAZ) and the base material (Fig. 3b). The hardness test measurements are presented in Tables 7, 8 and 9.

Chemical composition analysis

The analysis of the chemical composition was performed using optical spark emission

Table 4. Results of tests concerning the metal-mineral abrasive wear resistance of the joint specimens in the abrasion-resistant plates

Joint designation	Decrement of the volume of the abrasion-resistant layer of the joint, mm3* (decrement of the mass of the abrasion-resistant layer of the joint, g)						
	1	2	3	4	5	6	Mean value for individual levels
A	22.0585	20.3237	23.5397	21.7249	20.9642	22.6990	21.8850
B	24.4524	22.0537	25.1514	23.9589	23.1228	21.9030	23.4404
C	21.2319	22.3756	23.1694	24.5014	22.0392	22.5639	22.6469
In relation to all results							22.6574

*decrement of the volume of the abrasion-resistant layer of the joint was calculated in accordance with formula (1). The measured density of the abrasion-resistant layer of the joint in HARDPLATE 100S 5+3 made using the covered electrode with the solid core amounted to 7.4937 g/cm³, the density of the layer made using the flux-cored covered electrode amounted to 7.2958 g/cm³, whereas the density of the layer made using the self-shielded flux-cored wire amounted to 7.4322 g/cm³.

Table 5. Table of the analysis of variance

Name	Sum of squares S	Number of degrees of freedom f	Mean square s^2	Value of test F
Between systems MU	$S_{MU} = \sum_{i=1}^{K} r_i \bar{y}_i^2 - N\bar{y}^2 = 7.28599$	$f_{MU} = K - 1 = 2$	$s_{MU}^2 = \frac{S_{MU}}{K-1} = 3.6430$	$F = \frac{S_{MU}^2}{S_{WU}^2} = 2.5412$
Within systems WU	$S_{WU} = \sum_{i=1}^{K} \sum_{j=1}^{r_i} y_{ij}^2 - \sum_{i=1}^{r_i} r_i \bar{y}_i^2 = 21.50462$	$f_{WU} = N - K = 15$	$s_{WU}^2 = \frac{S_{WU}}{N-K} = 1.4336$	-
Rest R	$S_R = \sum_{i=1}^{K} \sum_{j=1}^{r_i} y_{ij}^2 - N\bar{y}^2 = 28.79062$	$f_R = N - 1 = 17$	-	-

where

r_i – number of measurements of the input factor at a given level;
N – total number of measurements of the input factor;
$\bar{y}_i$ – means of measurement results in the i-th line;
$\bar{y}$ – mean of all measurements;
y_{ij} – value of the j-th resultant factor at level i;
K – number of variability levels of the test factor.

Table 6. Results of the tests concerning the metal-mineral abrasive wear resistance of the abrasion-resistant plates

Designation of abrasion-resistant plate	Decrement of overlay weld volume, mm^3* (decrement of overlay weld mass, g)	Mean decrement of overlay weld volume, mm^3* (decrement of overlay weld mass, g)
D1	22.4222 (0.1684)	23.4874 (0.1764)
D2	21.6633 (0.1627)	
D3	25.2184 (0.1894)	
D4	23.6738 (0.1778)	
D5	23.0214 (0.1729)	
D6	24.9254 (0.1872)	

*decrement of the volume of the overlay welds was determined in accordance with formula (1).
The measured density of the overlay weld made in the HARDPLATE 100S 5+3 abrasion-resistant plate amounted to 7.5104 g/cm^3.

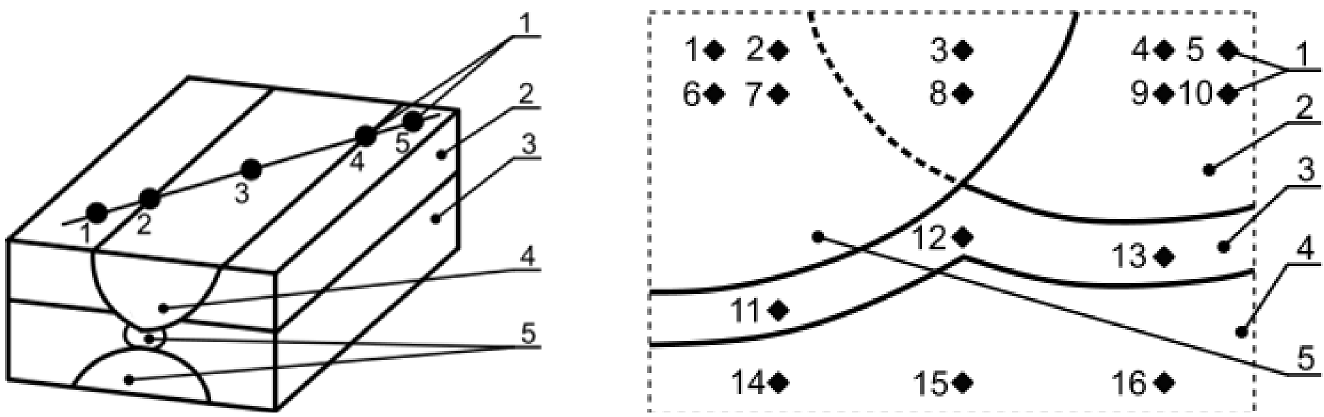


Fig. 3. Arrangement of hardness measurement points: a) on the surface of the face of the abrasion resistant layer (1 – hardness measurement points, 2 – surfaced layer, 3 – substrate material, 4 – run joining the surfaced layer, 5 – runs joining the substrate material); b) on the surface of the cross-section of the joint (1 – hardness measurement points, 2 – surfaced layer, 3 – heat affected zone, 4 – substrate material, 5 – run joining the surfaced layer)

Table 7. Test results concerning the HRC hardness on the surface of the face of the joint specimen and the abrasion-resistant plates

Specimen designation	Filler metal trade name	Hardness measurement point in accordance with Fig. 3a					Mean hardness value, HRC
		1	2	3	4	5	
A1	Hardface HC-E	59.5	61.0	61.5	60.5	60.0	60.5
A2	Hardface HC-E	60.0	58.0	60.5	60.0	59.5	59.6
A3	Hardface HC-E	61.0	60.0	61.0	61.0	61.5	60.9
A4	Hardface HC-E	62.5	62.0	59.0	60.5	60.0	60.8
A5	Hardface HC-E	61.0	60.0	62.5	62.5	58.5	60.9
A6	Hardface HC-E	59.5	62.5	60.0	61.0	59.0	60.4
B1	Hardface HC-TE	58.5	61.0	60.5	60.5	59.0	59.9
B2	Hardface HC-TE	61.5	61.5	61.0	60.5	60.0	60.9
B3	Hardface HC-TE	61.0	59.0	59.5	59.0	62.0	60.1
B4	Hardface HC-TE	60.0	58.5	58.5	60.0	61.0	59.6
B5	Hardface HC-TE	62.0	60.0	60.0	59.5	61.5	60.6
B6	Hardface HC-TE	61.0	59.5	59.5	62.0	58.0	60.0
C1	Hardface HC-O	58.5	62.5	62.5	61.5	61.5	61.3
C2	Hardface HC-O	61.5	62.0	61.0	59.5	62.0	61.2
C3	Hardface HC-O	61.5	60.0	61.0	62.5	60.0	61.0
C4	Hardface HC-O	59.5	59.5	60.5	60.0	61.5	60.2
C5	Hardface HC-O	58.0	60.0	62.0	61.5	61.5	60.6
C6	Hardface HC-O	60.0	59.0	60.0	60.5	58.5	59.6
D1	-	59.5	60.5	62.0	61.0	58.5	60.3
D2	-	58.0	59.0	59.0	59.5	60.5	59.2
D3	-	58.5	60.0	60.5	61.5	60.5	60.2
D4	-	61.5	60.0	62.5	58.0	60.0	60.4
D5	-	60.0	59.5	61.0	60.5	62.0	60.6
D6	-	59.5	61.5	60.5	59.0	61.0	60.3

Table 8. Results of HV30 hardness measurements of the abrasion-resistant layer on the surface of the cross-section of the joint specimen

Joint designation	Filler metal trade name	Hardness measurement point in accordance with Fig. 3b									
		1	2	3	4	5	6	7	8	9	10
A1	Hardface HC-E	707	784	713	774	752	694	786	683	764	622
B1	Hardface HC-TE	745	768	684	709	697	711	762	656	707	640
C1	Hardface HC-O	732	833	712	797	753	726	800	726	759	702

Table 9. Results of HV10 hardness measurements of the heat affected zone and the base material on the surface of the cross-section of the joint specimens

Joint designation	Filler metal trade name	Hardness measurement point in accordance with Fig. 3b					
		11	12	13	14	15	16
A1	Hardface HC-E	173	178	170	155	159	148
B1	Hardface HC-TE	166	161	171	142	151	140
C1	Hardface HC-O	177	189	182	168	163	169

Table 10. Results of the analysis of the chemical composition of the abrasion-resistant overlay weld

Joint designation	Filler metal trade name	Chemical composition, % by weight								
		Fe	C	Cr	Si	Mn	Ni	Mo	Nb	B
A1	Hardface HC-E	rest	4.15	22.72	1.49	0.83	0.11	0.04	0.01	0.16
B1	Hardface HC-TE	rest	4.16	23.47	1.35	0.74	0.11	0.04	0.01	0.08
C1	Hardface HC-O	rest	3.81	20.90	1.04	0.64	0.12	0.04	0.01	0.16

spectrometry. Each specimen (the ground surface of the face of the abrasion-resistant overlay weld) was subjected to three chemical composition analyses. The mean values of the contents of chemical elements are presented in Table 10.

The mean value (calculated using formula (2)) of the proportion of carbon and chromium ratio in the abrasion-resistant overlay weld in the joints of the HARDPLATE 100S plates to the contents of the same chemical elements in the weld deposit of a given filler metal amounted to 0.74 in relation to the covered electrode with the solid core; 0.75 as regards the flux-cored covered electrode 0.75 and 0.77 in terms of to the self-shielded flux-cored wire [12].

$$y_{zp} = \frac{\left(\frac{C_{sz}}{C_{sm}} + \frac{Cr_{sz}}{Cr_{sm}}\right)}{2}$$

where

y_{zp} – mean of the proportion of the content of carbon and chromium;

C_{sz} – content of carbon in the abrasion-resistant overlay weld of the joint, % by weight;

C_{sm} – content of carbon in the weld deposit of the filler metal, % by weight;

C_{rsz} – content of chromium in the abrasion-resistant overlay weld of the joint, % by weight;

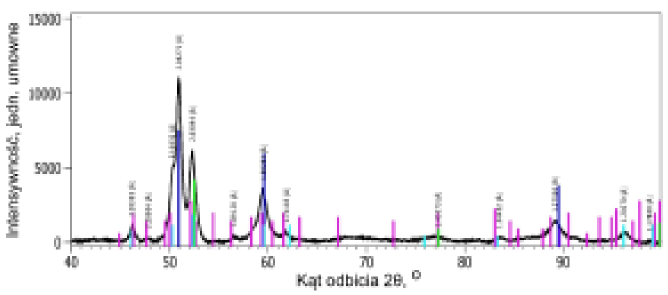
C_{rsm} – content of chromium in the weld deposit of the filler metal, % by weight.

Phase composition analysis

The analysis of the phase composition of the run joining the surfaced layer of the plates involved the use of an Empyrean X-ray diffractometer (PANalytical) and the filtered (filter Fe) radiation of a cobalt X-ray tube. The measurements were performed within the range of 20° to 100° of angle 2θ (corresponding to interplanar distance dhkl restricted within the range of 0.5145 nm to 0.1168 nm), with an increment of 0.026° 2θ and a counting time of 200 s. The phase identification was based on the database of International Centre for Diffraction Data PDF-4+ (year 2020). The phase identification results are presented in Figures 4a and 4b.

Metallographic tests

The determination of the quality of the joints made in the abrasion-resistant plates required the performance of macro and microscopic metallographic tests. The metallographic tests of the joints designated as A1, B1, C1 involved the cross-sectional metallographic specimen and were performed using a light microscope. The results of the macroscopic metallographic tests are presented in Figures 5a, 5b and 5c. The results of the microscopic metallographic tests are presented in Figures 6a, 6b, 6c and 6d.



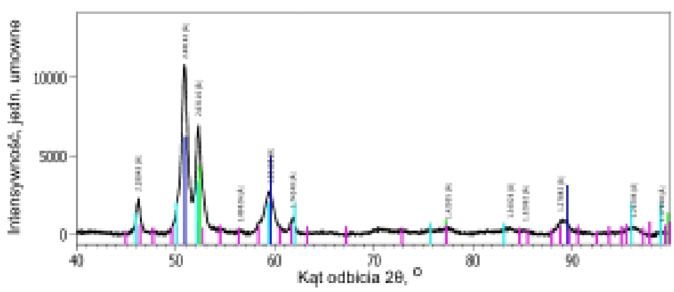


Fig. 4. XRD pattern of the abrasion-resistant run made using: a) covered electrode with the solid core (Hardface HC-E) and b) covered electrode with the flux core (Hardface HC-TE)

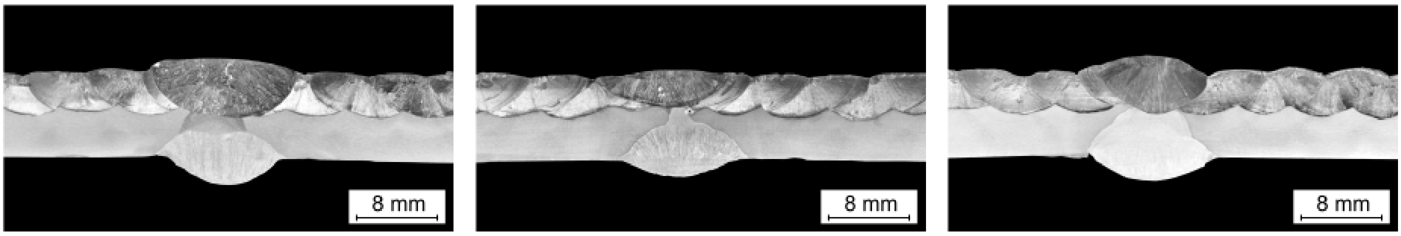


Fig. 5. Macrostructure of the joint in the abrasion-resistant plates made using: a) covered electrode with solid core (Hardface HC-E), b) covered electrode with flux core (Hardface HC-TE) and c) self-shielded flux-cored wire (Hardface HC-O)

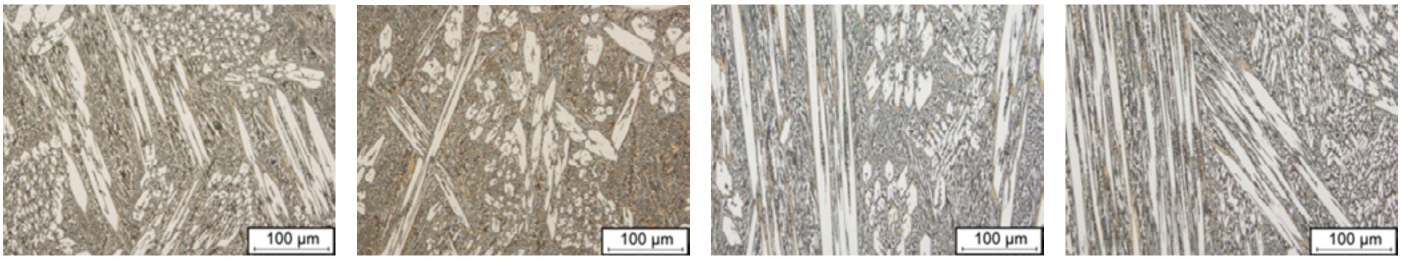


Fig. 6. Microstructure of: a) abrasion-resistant run made using the covered electrode with the solid core (Hardface HC-E); b) abrasion-resistant run made using the covered electrode with the flux core (Hardface HC-TE) and c) abrasion-resistant run made using self-shielded flux-cored (Hardface HC-O) and d) overlay weld made in the HARDPLATE 100S 5+3 abrasion-resistant plate

Analysis of test results

The tests concerning the abrasive wear resistance of the joints in the HARDPLATE 100S abrasion-resistant plates made using covered electrodes with solid core (Hardface HC-E) and covered electrodes with solid core (E 42 4 B 4 2 H5), covered electrodes with flux core (HC-TE) and covered electrodes with solid core (E 42 4 B 4 2 H5) as well as self-shielded flux-cored wire (Hardface HC-O) and metallic flux-cored wire (T 46 6 M M 1 H5) revealed that the abrasion-resistant layers were characterised by high abrasion resistance regardless of the applied welding technology. The mean decrement of the volume of the abrasion-resistant layer determined on the basis of the ASTM G 65 standard amounted to 21.8850 mm3 in relation to the joints welded using the electrode with the solid core (Hardface HC-E), 23.4404 mm3 in relation to the joints welded using the tubular electrode (Hardface HC-TE) and 22.6469 mm3 in relation to the joints welded using the self-shielded flux-cored wire (Hardface HC-O). Regardless of the form of the filler metal, the abrasion-resistant layers of the joints provided the metal-mineral abrasive wear resistance not lower than that of the overlay welds of the HARDPLATE 100S 5+3 surfaced plates. The variability coefficients related to the values of the decrements of the volume of the abrasion-resistant layers amounted to 4.84% in relation to welding performed using the covered electrode with the solid core, 5.11% in relation to welding performed using the tubular electrode and 4.48% in relation to welding performed using the self-shielded flux-cored wire. The calculated values of the variability coefficients indicated the homogenous abrasion resistance of the individual variants of the joints. The tests concerning the significance of the effect of a given welding technology on the abrasive wear resistance of the joints of the abrasion-resistant plates was performed using the completely randomised design. The value of test F, calculated on the basis of the statistical analysis of the test results (Table 5), was lower than critical value F0.05; 2; 15 of the Fischer-Snedecor F test [10]. The foregoing justified the conclusion that, in relation to the adopted level of significance and the calculated numbers of the degrees of freedom, the welding technology did not significantly affect the metal-mineral abrasive wear resistance of the abrasion-resistant layers of the butt joints of the plates with the overlay weld having the structure of the high-alloy chromium cast iron.

The hardness measurements involving the surface of the face of the abrasion-resistant layers of the joints revealed the high hardness of the latter and the high repeatability of results, regardless of the form of the filler metal used for the joining of the overlay welds of the plates. In relation to individual specimens, the mean hardness values were restricted within the range of 60.2 HRC to 60.8 HRC, with the range amounting to 4.5 HRC. No decrease in the hardness of the abrasion-resistant layer in the weld run and in the area of contact between the aforesaid run and the run of the overlay weld was observed in relation to any welding variant. The hardness of the overlay welds of the abrasion-resistant plates measured on the cross-sectional surface was restricted within the range of 622 HV30 to 797 HV30. The hardness of the abrasion-resistant run and the zone of its contact with the surfaced layer of the plate was restricted within the range of 694 HV30 to 786 HV30 and 683 HV30 to 713 HV30 in relation to joint A1, 711 HV30 to 768 HV30 and 656 HV30 to 684 HV30 in relation to joint B1 and 726 HV30 to 833 HV30 and 712 HV30 to 726 HV30 in relation to joint C1. The hardness of the heat affected zone in the base material of the welded joints was restricted within the range of 161 HV10 to 189 HV10, whereas the hardness of the base material was restricted within the range of 140 HV10 to 169 HV10. In both cases, the measured value did not exceed the maximum permissible hardness value of 380 HV10 in accordance with PN-EN ISO 15614-1:2017-08 in relation to steels from material group 1 not subjected to heat treatment.

Regardless of the filler metal form, all of the abrasion-resistant runs provided the chemical composition of alloy Fe15. The abrasion-resistant welds made using the tubular electrodes were characterised by the higher content of carbon and that of chromium than one-layer multi-run overlay welds surfaced manually using the same filler metal on the plate made of steel S355 [13]. In the conventional technique of the deposition of one-layer multi-run overlay welds involving the shifting of the electrode after making a run, the partial melting of the substrate material is greater than during the deposition of the run joining the abrasion-resistant layers of plates. The above-presented situation was triggered by the two-sided limitation of the weld pool by the runs of the overlay welds of the abrasion-resistant plates belonging to the same group of alloys (Fe15). The abrasion-resistant runs of the joints of the plates made using the covered electrode with the solid core or the flux-cored wire will also probably be characterised by the higher contents of carbon and chromium than the one-layer multi-run overlay welds deposited using similar technological parameters. The mean of the proportion of the contents of carbon and chromium in the abrasion-resistant welds of the joints to the contents of the aforesaid chemical elements in the weld deposit of a given filler metal amounted to 0.74 in relation to the covered electrode with the solid core, 0.75 in relation to the flux-cored covered electrode and 0.77 in relation to the flux-cored wire.

The metallographic tests did not reveal the presence of welding imperfections in any of the joints subjected to analysis. The joint made using the electrodes with the solid core and made using the flux-cored electrode (designated as B1) was characterised by the partial melting of the abrasion-resistant layer by the penetration run, which was probably responsible for the formation of a single gas pore in the penetration area. The measured diameter of the pore amounted to approximately 0.2 mm and did not exceed the limit value related to quality level B in accordance with PN-EN ISO 5817:2014-05. Gas pores are acceptable in the surfaced layer of the abrasion-resistant plates exposed to metal-mineral abrasive wear [7]. The excessive partial melting of the overlay weld of the abrasion-resistant plate by the run joining the substrate material results in the cracking of the run [3]. None of the test joints contained cracks in the penetration run. The thickness of the abrasion-resistant run made using the covered electrode with the solid core, the tubular electrode and the flux-cored wire amounted to 5.4 mm, 3.4 mm and 5.3 mm respectively. In all of the joint variants, the measured thickness of the run joining the surfaced layer was greater than the thickness of the overlay welds of the HARDPLATE 100S 5+3 plates declared by the manufacturer [5].

The chemical composition analysis, the analysis of phase composition as well as the microscopic tests revealed that in all of the joint variants the structure of the abrasion-resistant run was composed of Cr_7C_3 and $(Fe,Cr)_7C_3$ carbides in the matrix consisting of austenite with a slight amount of ferrite. The microscopic metallographic tests did not reveal differences in the structure of the abrasion-resistant runs of the joints and in surfaced layer of the HARDPLATE 100S plates.

Concluding remarks

The tests concerning the technology used in the welding of the plates with the abrasion-resistant overlay weld (HARDPLATE 100S 5+3) justified the formulation of the following conclusions:

1. In relation to the adopted level of significance and the calculated numbers of the degrees of freedom, the arc welding technologies subjected to analysis did not significantly affect the metal-mineral abrasive wear resistance of the abrasion-resistant layers of the joints of the plates with the overlay weld having the structure of the high-alloy chromium cast iron. Regardless of the form of the filler metal, the abrasion-resistant layers of the joints provided the abrasive wear resistance not lower than that of the overlay welds of the HARDPLATE 100S 5+3 surfaced plates
2. The applied arc welding technologies involving the use of the covered electrodes with the solid core, covered electrodes with the solid core and the flux core as well as self-shielded flux-cored wires enabled the obtainment of the joints free from welding imperfections. In all of the joint variants the structure of the abrasion-resistant run was composed of Cr_7C_3 and $(Fe,Cr)_7C_3$ carbides in the matrix consisting of austenite with a slight amount of ferrite.

References:

[1] Mucha T., Bartkowiak K.: Zastosowanie napawanych płyt trudno ścieralnych w naprawach maszyn podstawowych górnictwa odkrywkowego. Przegląd Spawalnictwa, 2011, vol. 83, no. 10, pp. 73–76.

[2] Neale M., Gee M.: A guide to wear problems and testing for industry. William Andrew, 2001, pp. 3–8.

[3] Górka J., Kik T., Czupryński A., Foreiter W.: Technologia spawania płyt trudno ścieralnych. Biuletyn Instytutu Spawalnictwa, 2011, no. 3, pp. 29–33.

[4] Szymura M., Różański M.: The influence of positioning deposited beads towards direction of abrasive movement, to resistance on grind wear plates' abrasive wear. Welding Technology Review, 2019, vol. 91, no. 5, pp. 11–16.

[5] Materiały informacyjne firmy Welding Alloys Polska Sp. z o.o., 2020.

[6] Adamiec P., Dziubiński J., Turyk E.: Spawalnicze metody nanoszenia warstw, in: Pilarczyk J. (red.): Poradnik inżyniera. Spawalnictwo vol. 2. Wydawnictwa Naukowo-Techniczne, Warszawa, 2005, pp. 719–720.

[7] Riabcew I. A, Rosert R., Senczenkow I. K., Turyk E.: Niezgodności spawalnicze warstw napawanych. Biuletyn Instytutu Spawalnictwa, 2017, no. 3, pp. 26–35.

[8] Wang Z. H., Wang Q. B., Cui L., Yang A. D., He D. Y.: Influence of cooling rate and composition on orientation of primary carbides of Fe–Cr–C hardfacing alloys. Science and Technology of Welding and

Joining, 2008, vol. 13, no. 7, pp. 656–662.
[9] Poloczek T., Czupryński A.: Analiza odporności na zużycie ścierne i erozyjne płyt trudno ścieralnych. Biuletyn Instytutu Spawalnictwa, 2019, no. 3, pp. 29–34.
[10] Kukiełka L.: Podstawy badań inżynierskich, Wydawnictwo Naukowe PWN, 2002, pp. 40–42, 248.
[11] https://www.random.org/sequences/ (accessed on 28.05.2020)
[12] Zorc M., Nagode A., Kosec B., Zorc B.: Determining the degree of admixing rate of the base material and the melting efficiency in single-bead surface welds using different methods, including new approaches. Materials, 2019, vol. 12, no. 9, 1479.
[13] Szymura M., Czuprynski A., Różański M.: Research on the properties of high chromium cast iron overlay welds deposited by tubular electrodes. Welding Technology Review, 2018, vol. 90, no. 10, pp. 26–30.