J. Min. Metall. Sect. B-Metall., 56 (2) (2020) 209 - 220

Journal of Mining and Metallurgy,
Section B: Metallurgy

ASSESSMENT OF THE QUALITY OF ABRASION-RESISTANT PLATES WELDED JOINT

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(Received 24 September 2019; accepted 12 May 2020)

Abstract

The article presents the analysis of the structure and properties of joints made of abrasion-resistant plates having the structure of chromium cast iron and welded with filler metals, the use of which aimed to provide the high abrasion resistance of the surface layer and good mechanical properties of the base material. The face layer of the joint was made using the MMA (Manual Metal Arc) welding method and the Fe-Cr-Nb-B type nanocrystalline filler metal. The root weld was welded using an austenitic filler metal, whereas the filling layer was welded using the MAG method with a low-alloy filler metal. The joints were subjected to non-destructive tests (visual tests and penetrant tests) as well as to mechanical properties tests. The research involved macro and microscopic metallographic tests, the determination of the grain size using an Xpert PRO X-ray diffractometer, and the EDS analysis of the chemical composition of the precipitates. The assessment of the operational properties of the joints based on hardness measurements, static tensile tests, bend tests as well as identifying the metal-mineral abrasive wear resistance were performed in accordance with ASTM G65 – 04 standards. The results of the abrasion resistance tests were referred to the HARDOX 400 steel reference specimen. Considering the tests results it was concluded that the used filler materials can assure the appropriate operational properties of welded abrasion-resistant plates.

Keywords: *Abrasion; Abrasion-resistant plates; Welding; Nanocrystalline filler metal*

1. Introduction

A relevant scientific, technical, and economic issue is the wear of machinery elements caused by a decrease in the functional properties of the work surface. In most cases, wear mechanisms are very complex and involve many interrelated factors the intensity of which depends on a work environment and conditions. The variety of types of wear necessitates the specialisation of structural materials to provide the highest possible wear resistance to surface layers exposed to specific operational conditions [1-7]. One of the commonly used type of materials are abrasion-resistant plates. The structure of the surface layer and its properties are of great importance regarding the service life of individual machinery elements [8-11]. At times characterized by the very intense operation of machinery parts, the search for new material groups must also take economic aspects into consideration. The progressive implementation of new material solutions must involve due care and be preceded by both in-depth and thorough analysis. The foregoing also applies to the implementation of a new group of materials resistant to abrasion, i.e. abrasion-resistant plates and tubes. The above-named group constitutes a new generation of abrasion-resistant materials, which, obtained in a highly complex production process, have found applications in the metallurgical, mining, and automotive industries as well as in foundries, sand excavation, waste disposal, power plants, and in the operation of machinery parts and equipment [12-16]. Abrasion-resistant plates are characterized by good weldability, toughness, and mechanical workability, thus offering the combination of high hardness with high resistance to mechanical loads. The use of abrasion-resistant plates in the production of elements exposed to intensive abrasive wear leads to significant material savings resulting from the reduction of production costs due to shorter equipment and machinery idle times, and the consequence is lower frequency of replacing worn machinery parts. The above-named plates are multilayer linings characterized by the easy fixing procedure as well as by high resistance to abrasive wear and erosion. They are made by coating an easy-to-weld base plate with an abrasion-resistant layer. The unique abrasive wear resistance of the plates is obtained through the presence of very hard carbide phases (1500-3000 HV) in the surface layer. The aforesaid carbides are 2-3 times harder than the most commonly used abrasive materials. Abrasion-resistant plates can be subjected to underwater

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https://doi.org/10.2298/JMMB190515010G

plasma cutting, bending, and joining, enabling the making of fragments of abrasive-resistant linings and machinery parts. The aforementioned plates can be used not only as flat elements protecting surfaces exposed to intensive wear but, because of the good weldability of the undercoat and the bendability up to a diameter of 400 mm, can be also used to make complex structures [16-22]. Regrettably, the welding of the above-named elements is accompanied by problems with providing appropriate operational properties of the face layer of the overlay weld. The recent several years have seen a dynamic rise in the intensity of research works focused on the development of new filler metals enabling the making of layers characterized by unique structures and properties, different from those of previously made layers (particularly in terms of hardness, impact load resistance, and a low friction coefficient) [23-26]. The dynamic development of nanostructured materials foreshow a future increase in their use in welding technologies. Because of the different properties of nanostructured materials (especially when they are compared with the steels), their use in welding and surfacing technologies provides new possibilities. Nanomaterials are single-phase or polyphase polycrystals, with the grain size restricted within the range of 1 x 10^{-9} m to 250 x 10^{-9} m. As regards the upper limit of the above-named limit, a more popular term is the "very fine grain size" (i.e. restricted within the range of 250 nm to 1000nm). Nanostructured crystalline materials are characterized by a significant volume fraction on grain boundaries, which significantly changes their physical, chemical, and mechanical properties in comparison with conventional coarse-grained materials, the size of which is usually restricted within the range of 10 µm to 300 µm [26-29]. Nanomaterials used when making coatings and nanostructured layers are characterized by considerably higher abrasion resistance than that of traditional steel-based materials. However, because of high costs and the ongoing development of their production technology, nanostructured materials are not widely used in surfacing [30-37].

2. Individual research

The individually performed research-related tests were aimed to assess the operational properties of welded joints made of abrasion-resistant plates (Fig. 1, Table 1, 2). The abrasion resistant plate was welded on the low-alloy steel substrate by using a covered electrode (for welding a root layer) and the Fe-Cr-Nb-B type nanocrystalline filler metal in case of welding the abrasive wear resistant layer. The

Table 1. *Chemical composition and typical hardness of the abrasive wear resistant layerwork [9]*

Contents of chemical compositions, wt. %				
C	Cr	Nb	B	Fe
5.2	22	7	1.8	rest
The average hardness is 68 HRC (matrix hardness approx. 850 HV30 with max.				
1500-3000 HV for present hard phases).				

Table 2. *Chemical composition and mechanical properties of the base material (S235JR) work [9]*

Contents of chemical compositions, wt. %				
C	Mn	P	S	N
0.17	1.4	0.035	0.045	0.009
Mechanical properties				
The yield point	Tensile strength R_m	Elongation	Impact strength	
$R_{e\ min}$ [MPa]	[MPa]	$A_{5\ min}$ [%]	KV_{min}	
235	470	26	57	

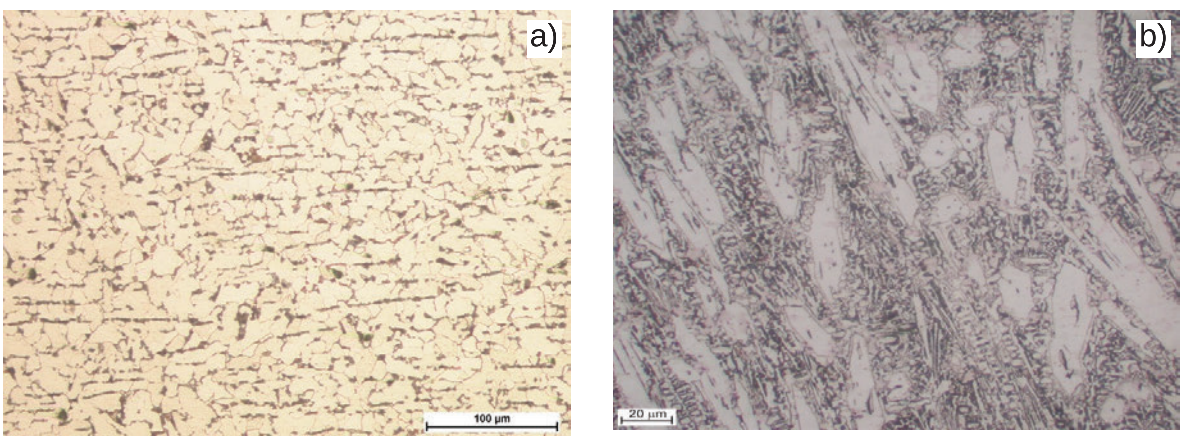

Figure 1. *Structure and the microstructure of the test abrasion-resistant plates: (a) ferritic-pearlitic microstructure of the base of the abrasion-resistant plate, (b) microstructure of the chromium cast iron of the layer resistant to abrasive wear*

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obtained abrasion resistance properties of the tested layer are the result of the alloying with Nb and B and formed microconstituents. They lead to the fragmentation of grain into nanocrystalline size, which increases the strength properties and can contribute to increased abrasion resistance. The rest of the joint was filled using the MAG method and a low-alloy filler metal.

2.1 Technology for the welding of abrasion-resistant plates

The joints were welded with three beads. The first (root) and third bead (joint the abrasion resistant layer) were made with coated electrodes (MMA). The second (filling) bead was made using the MAG method. The welding of the base of the abrasion-resistant plate was performed using covered electrodes and the austenitic filler metal as well as using the MAG method and the low-alloy filler material. The abrasive wear resistant layer was made using electrodes covered with the Fe-Cr-Nb-B type nanocrystalline structured filler metal, the chemical composition of which is presented in Table 3.

According to the data provided by the producer, the weld deposit of the Fe-Cr-Nb-B type nanocrystalline electrodes is composed of very hard fractions of boron carbide arranged uniformly in the semi-amorphous iron alloy. The weld should be characterized by high abrasive wear resistance and high resistance to dynamic loads. The electrode deposit had a hardness of about 67-70 HRC. The preparation of the plate and the welding sequence are presented in Figure 2, welding parameters are presented in Table 4, whereas the welded joint is presented in Figure 3. Applied preheating operation removes the moisture and dirt that can be the reason for the development of cold cracks in the area of the wear plate.

2.2. Tests of welded joints

The test joints were subjected to the following non-destructive tests:

- visual tests according to the ISO 17637:2011 standards; the tests were carried out on the side of the face and root of the weld. The distance of the observer's eye from the test surface was 600 mm, the viewing angle was 30 degrees, and the intensity of light was 500 lx;
- fluorescent penetrant tests according to the ISO 3452-1:2013-08 standards; the tests were carried out on the side of the face and ridge of the weld using UV fluorescent penetrant technique. The intensity of UV-A radiation was 10 W/cm^2, the intensity of light was 20 lx.

After the non-destructive tests, the test joints were prepared for the following destructive tests:

- tensile tests performed in accordance with ISO 6892-1:2010 standard, involving the use of a ZWICK/ROELL Z 330RED testing machine and specimens sampled in accordance with ISO 4136:2011, the samples were cut from the welded joints using a plasma cutting process and then machined;

Table 3. *Chemical compositions of the filler metals used in the making of the welded joint*

Chemical composition, wt. %								Weld deposit hardness
C	Cr	Ni	B	Nb	Mn	Si	Fe	
Face abrasive wear resistant layer								
1.4	15.2	-	4	3.4	0.4	0.4	balance	68÷70 HRC
Root layer								
0.2	19	9	-	-	7	1.5	balance	-
Filling layer								
0.1	-	-	-	-	1.7	1	balance	-

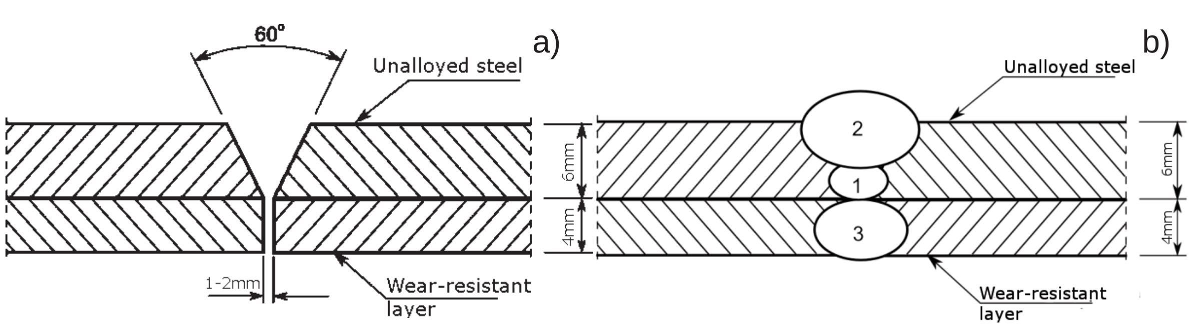

Figure 2. *(a) Weld groove preparation of plates, and (b) welding sequence*

Table 4. *Parameters used during the welding of the abrasion-resistant plate*

Plate designation	Bead number designation	Welding process designation	Diameter of electrode/wire	Arc voltage	Current [A]	Filler metal
			[mm]	[V]		
P1	1	111	3,2	26	100	Austenitic filler material
	2	135	1,0	24	230	Low-alloy filler material
	3	111	3,2	26	100	Nanocrystalline structure
Remarks: welding current type: DC (+), welding position: flat (PA), angle between electrode and welded plate surface: 90°, surface preparation before welding: grinding and preheating (with a gas torch) up to a temperature of approximately 80 °C.						

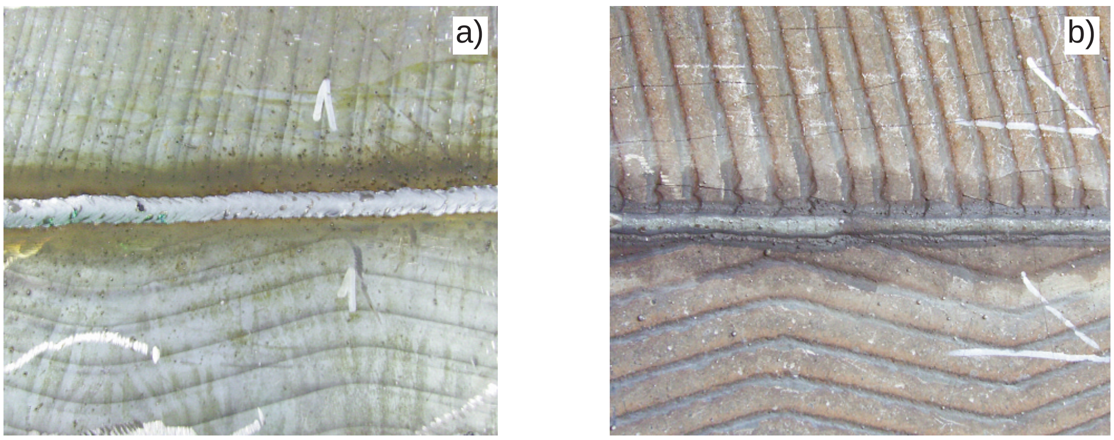

Figure 3. *Welded joint (a) view from the base material side, (b) view from the side of the abrasive wear resistant layer*

- face bend test of the butt weld (FBB) and the root bend test of the butt weld (RBB) according to the ISO 5173:2010 standard. The aforesaid bend tests were performed using the ZWICK/ROELL Z 330RED testing machine provided with an additional module for bend tests, involving the use of a bending mandrel having a diameter of 30 mm. The distance between the rollers amounted to 60 mm. To identify the position of the specimen face weld axis, the tested specimens were etched in Adler's reagent;
- macrographic examinations were performed on an Olympus SZX9 light microscope; the tests specimens were etched in Adler's reagent;
- microstructure metallographic examinations were performed on a NIKON ECLIPSE MA100 light microscope; the tests specimens were subjected to etching in Nital;
- cross-sectional hardness measurements were performed using a Vickers 401MVD testing machine (Wilson Wolpert) under a load of 1 kg; the hardness measurements of the weld face were performed using the Rockwell method and a Zwick Roell ZHR testing machine;
- measurements of the grain size of the nanocrystalline microstructure of Fe-Cr-Nb-B were performed using an Xpert PRO PANalytical X-ray diffractometer and a computer-aided radiation recording system equipped with a cobalt anode lamp,
- chemical composition of precipitates was determined using an energy dispersive X-ray spectroscopic (EDS) EDAX detector and a Zeiss Supra 35 scanning electron microscope (SEM),
- tests concerning resistance to the metal-mineral type abrasive wear were performed in accordance with the ASTM G 65-00 standard; the reference material being a plate made of abrasive-resistant steel grade Hardox 400.

3. Results and Discussion

The visual and the fluorescent penetrant tests revealed that the welded joint on the base material side was free from cracks. The abrasion-resistant layer and the weld face contained cracks characteristic to the structure of abrasive wear resistant plates; the above-named cracks did not reduce operational properties (Fig. 4). It is because abrasive particles may also accumulate in the cracks from the abrasive-resistant side, which can reduce the wear.

The results of the macroscopic metallographic tests of the welded joint indicate that the welding of the root

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run was accompanied by the slight partial melting and the mixing of the filler material, base material, and the abrasive wear resistant material (Fig. 5). In the case under discussion, the fusion line was regular, i.e. without the excessive partial melting of the abrasion-resistant layer. In addition, in the layer resistant to abrasive wear, the macroscopic tests revealed the presence of the cracks, typical of the weld deposit type.

The analysis of the microscopic examinations results obtained by using the light technique indicate the heterogeneity of the joint (Fig. 6).

The structure of the weld joining the abrasion resistant layer was characterized by the fine-grained structure with numerous carbide precipitates (Fig. 7a); the central part of the joint revealed the mixing of the filler with the base material. The root layer was characterized by the austenitic structure (Fig. 7b), whereas the filling layer contained the ferritic-pearlitic structure (Fig. 7c).

The tests performed using an electron microprobe X-ray analyser revealed that the weld area contained easily visible niobium carbides, whereas the chromium formed carbide eutectics (Fig. 8).

The welding process resulted in the melting of the material of the abrasive wear resistant layer, the passage of carbides to the weld as well as in the partial and non-uniform mixing of the material (Fig. 9).

The analysis concerning the distribution of alloying elements in the weld confirmed the previously obtained test results and revealed the non-uniform arrangement of the niobium and chromium in the weld area (Fig. 10).

The measurement of the grain size in relation to the Fe-Cr-Nb-B type crystallographic nanocrystalline microstructure was performed using an Xpert PRO X-ray diffractometer (PANalytical) and a computer-aided radiation recording system equipped with a cobalt anode lamp (40 [kV] voltage, 30 [mA] heater current, and a strip detector (angular range of 30 to 120 [°]). The calculations concerning the size of crystallites, performed using the Scherrer equation (1), revealed that the mean grain size in the face layer microstructure, measured perpendicularly in relation to the base, amounted to approximately 20 [nm].

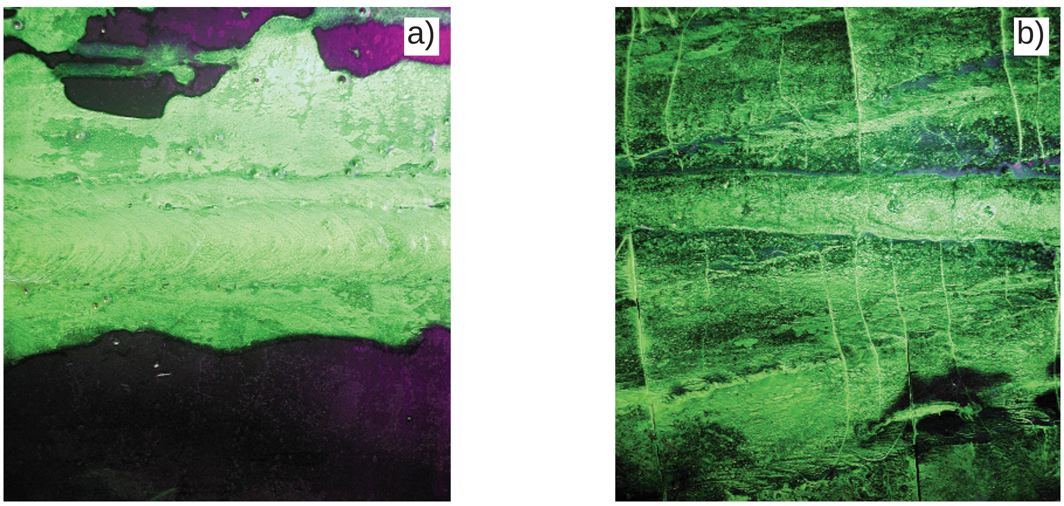

Figure 4. *Test joint during the penetrant test (a) view from the root side, (b) and the view from the side of the abrasion resistant layer*

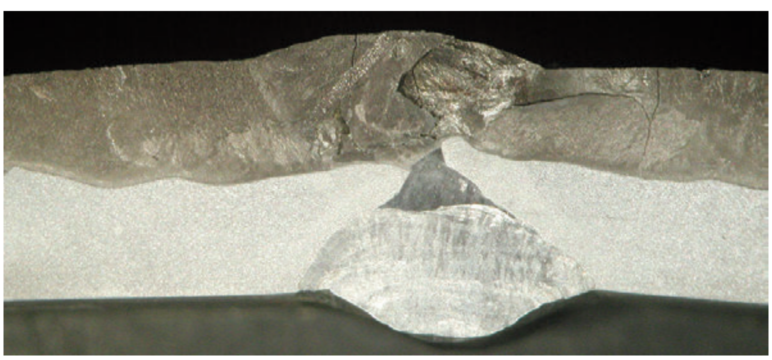

Figure 5. *Macrostructure of the welded joint*

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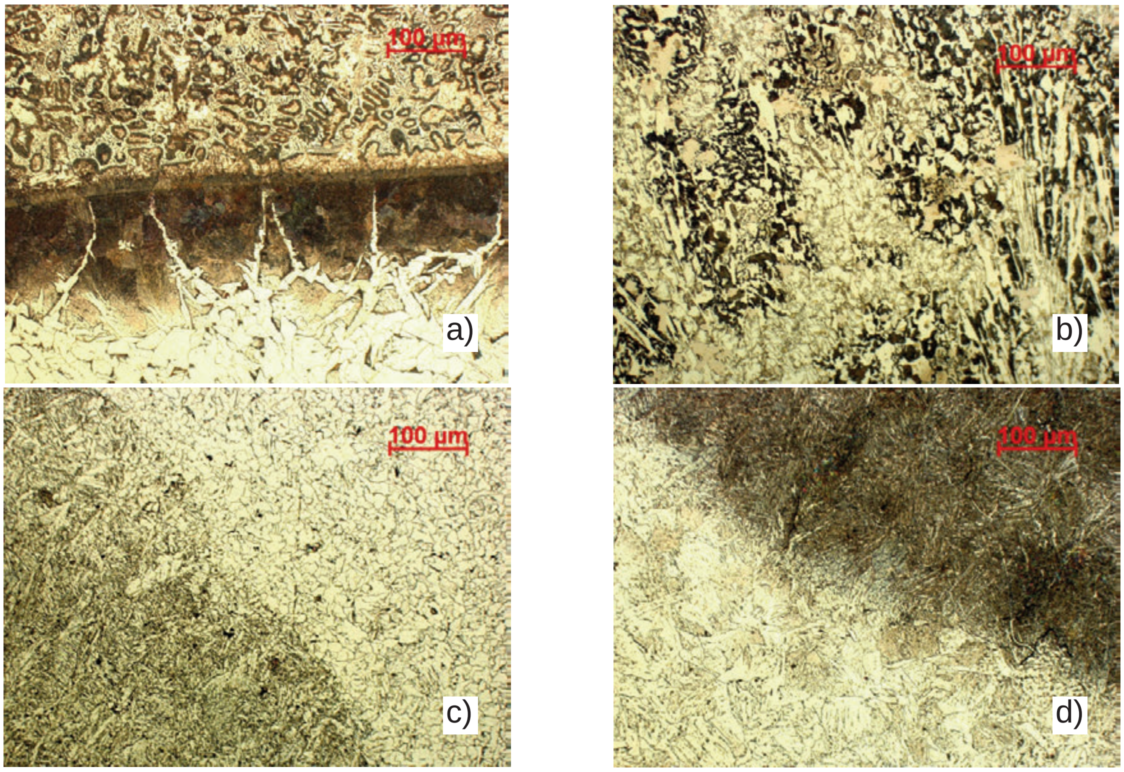

Figure 6. *Microstructure of the welded joint (a) interface between the abrasion-resistant layer and the unalloyed steel, (b) niobium carbides present in the matrix, (c) transition zone between the weld and the HAZ of the substrate material, (d) transition zone between the weld and the substrate material*

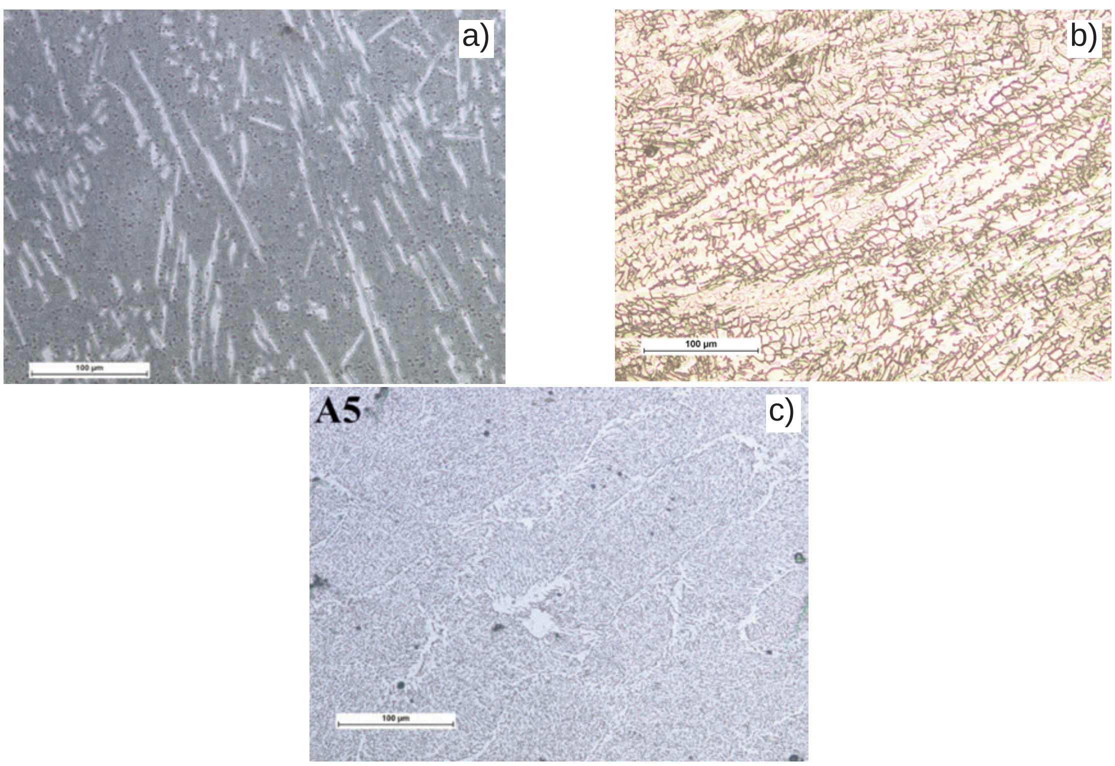

Figure 7. *Microstructure of the welds: a) abrasive wear resistant layer, b) weld root, c) filling weld bead*

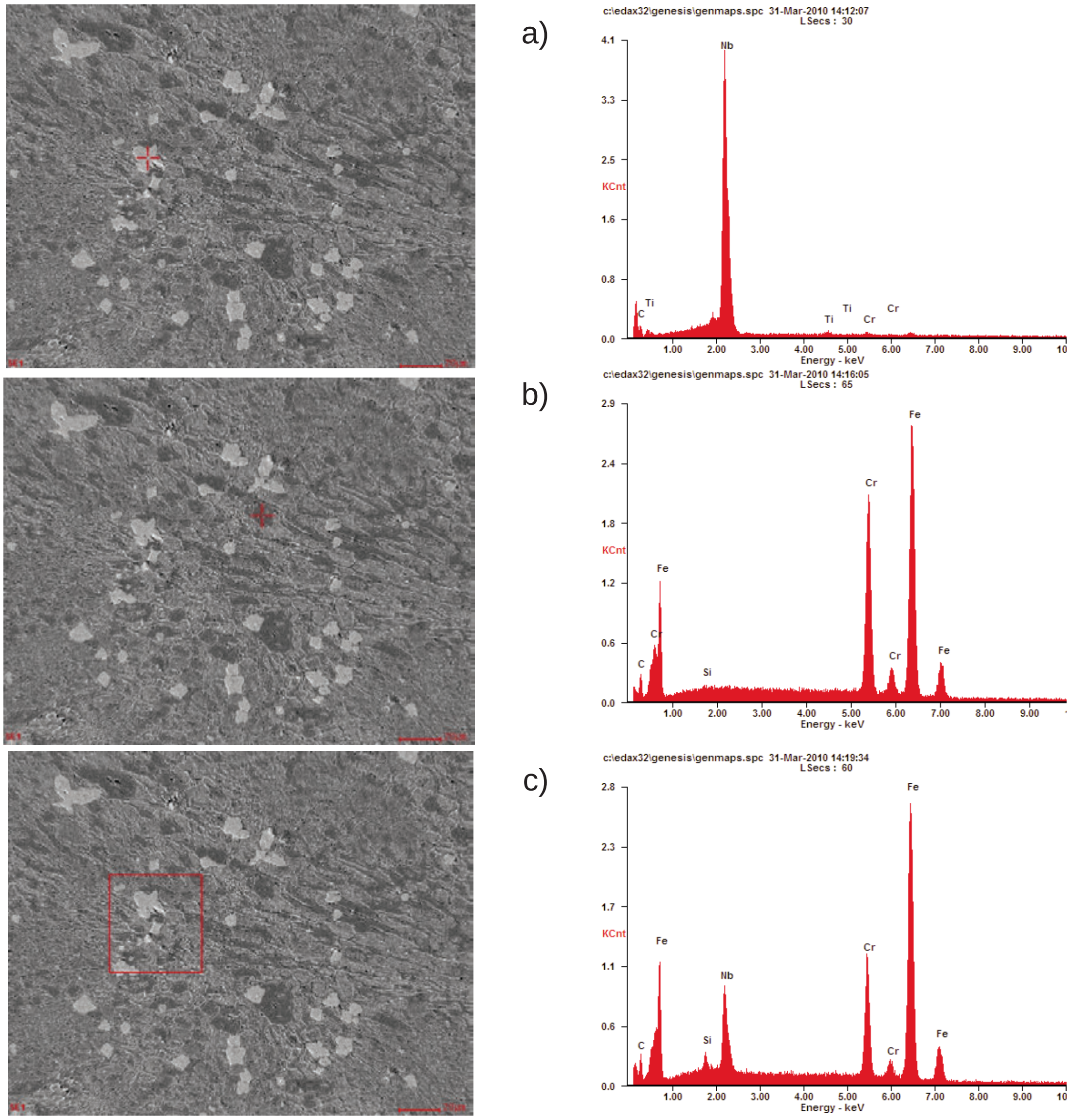

Figure 8. *Microstructure of the test weld along with the diagram of dispersed X-radiation energy: (a) niobium carbide precipitations, (b) chromium eutectics, (c) matrix material*

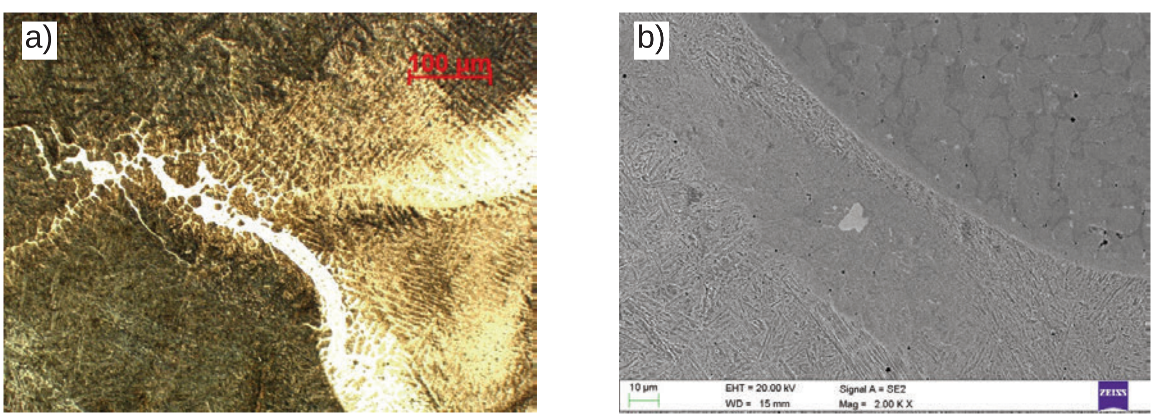

Figure 9. *Mixing of the weld and the material of the abrasive wear resistant layer (a) image from light microscopy, (b) scanning electron micrograph*

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$$D = \frac{K \cdot \lambda}{B_{struct} \cdot \cos\theta} \quad (1)$$

where D – mean size of the crystallite in the perpendicular direction in relation to the bend plane, K – Scherrer constant (close to unity), λ – wavelength, B_{struct}. – rate of reflection, θ – Bragg angle in relation to reflection.

Table 5. *Types of carbides occurring in the face layer*

Type of carbid	Cr_7C_3	$Cr_{23}C_6$	NbC
Lattice plane	(002), (151),(321), (202), (222), (260), (081)	(400), (420), (422), (333), (440), (531), (620), (911)	(111), (200), (220)

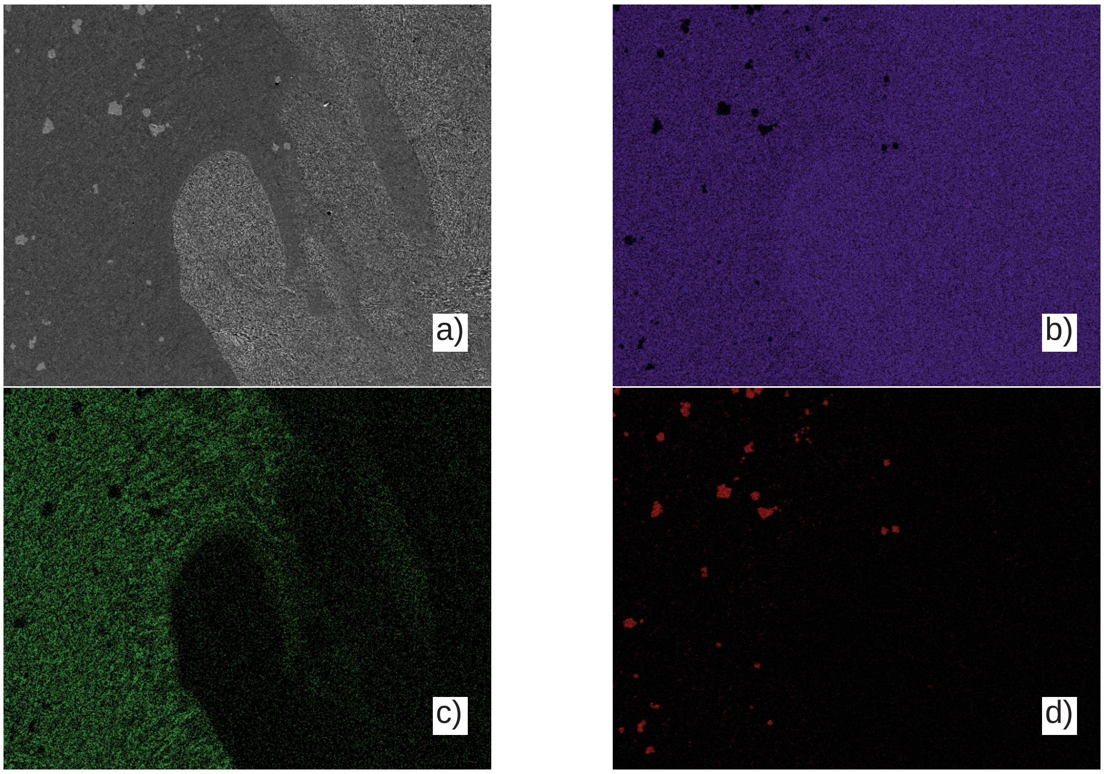

Figure 10. *Surface distribution of alloying elements in the weld area: (a) mixing area, (b) iron distribution, (c) chromium distribution, (d) niobium distribution*

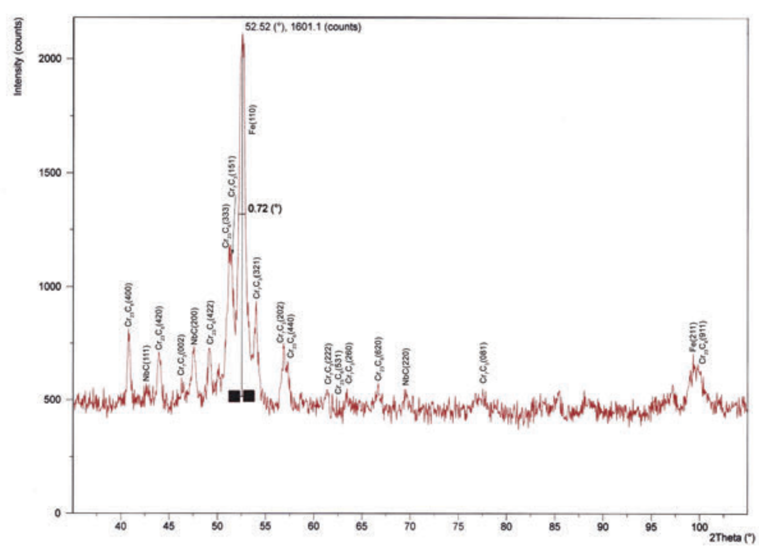

Figure 11. *XRD patterns of the weld face layer*

The analysis of XRD patterns of the face layer revealed the presence of reflections related to three types of carbides, Table 5, Figure 11.

The HV1 hardness tests performed on the cross-section of the joint (Fig. 12) revealed a hardness approximately about 800 HV1 in the base material on the side of the abrasion-resistant layer and 920 HV1 in the area of the weld made using the nanocrystalline weld deposit. The HV1 hardness measurements involving the cross-section of the base material revealed a hardness about 140 HV1 and approximately 180 HV1 in the root layer, Table 6.

The Rockwell hardness tests measurements revealed a hardness of about 70 HRC. The mean hardness value on the surface of the test plate amounted to 62 HRC. The tensile test revealed that the welded joint was characterized by a strength of 370 MPa (Table 7, Figure 13). In each case, the specimen ruptured outside the weld area. Because of the structure of the abrasion-resistant plate, the tensile strength should be determined for the cross-section excluding the thickness of the abrasive wear resistant layer. The bend angles obtained in the RBB and FBB amounted to 55^o and 85^o (Table 8, Figure 14).

The analysis concerning the resistance of the face layer to abrasive wear was based on the metal–mineral type abrasive wear resistance tests performed in accordance with ASTM G65 – 04, procedure A. The reference material used in the tests was abrasive wear resistant steel grade Hardox400. The abrasion wear tests were performed using the gravimetric method in metal-dry mineral friction conditions. During the tests, the specimen was fixed in a special clamp pressing the specimen against a rubber wheel having a diameter of 228.6 mm. The test specimen was pressed against the

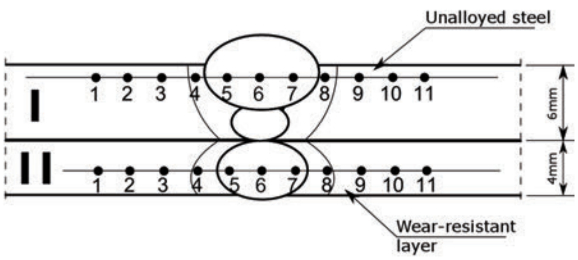

Figure 12. *Hardness measurement points distribution*

Table 7. *Results of the tensile tests of the abrasion-resistant plates*

Specimen designation		Cross-section S_0, mm^2	Breaking force F_m, kN	Tensile strength R_m, MPa	Rupture location
Joint P1	R/1	168	60.21	360	outside the weld
	R/2	168	63.02	371	outside the weld

Table 6. *Results of the HV1 hardness tests in relation to the cross-section of the welded joint*

Hardness HV1												
Specimen	Measurement	1	2	3	4	5	6	7	8	9	10	11
P1	I	144	151	148	160	178	184	187	156	147	150	146
	II	806	808	812	932	924	912	939	918	809	810	808

Figure 13. *View of welded joints after a tensile test with fractures*

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aforesaid wheel; the force applied during the test amounted to 130N. The abrasive material in the form of granular sand was supplied (by means of a nozzle) to the area of contact between the specimen and the rubber wheel. The abrasive material was fed at a flow rate restricted within the range of 300 g/min to 400 g/min. The wheel rotated in the direction consistent with the abrasive material feeding direction. The wheel rotated at a rate of 200 rpm and made 6000 rotations. The tests involved 2 specimens having dimensions 25×75×10 mm. The mass decrement was determined using a laboratory balance at an accuracy of up to 0.0001g. The density was measured using the pycnometric method. The mean density of the weld made using the nanocrystalline filler metal amounted to 8.78 [g/cm^3], whereas the mean density of the abrasion-resistant plate amounted to 7.17 [g/cm^3]. The mean decrement of the volume of the test material was determined using formula (2):

$$\textit{Volume decrement},\ [mm3\ ] = \textit{mass decrement}\ [g]\ :\ \textit{density}\ [g/cm3]\ x\ 1000 \qquad (2)$$

The face layer, made by using the Fe-Cr-Nb-B type filler metal of the nanocrystalline structure was 11 times more resistant to the metal-mineral type abrasive wear than reference steel Hardox 400 and approximately 1.5 time more resistant to the above-named wear than the abrasion–resistant plate (Table 9, Fig. 15).

Table 8. *RBB and FBB test results related to the welded joints made of the abrasion-resistant plates*

Specimen		Bend side	Bend angle, °	Remarks
Joint P1	FBB1	Face	55	rupture in the HAZ
	FBB2	Face	55	rupture in the HAZ
	RBB1	Root	85	rupture in the HAZ
	RBB2	Root	85	rupture in the HAZ

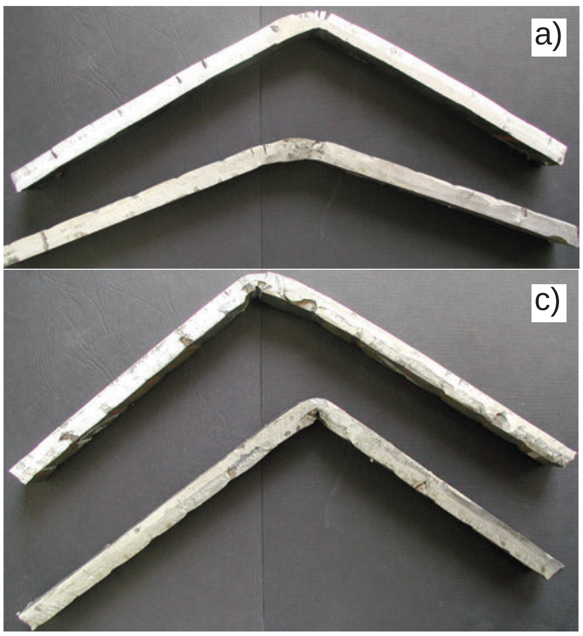

Figure 14. *View of welded joints after bending test: (a) bending test with tensile of the wear layer, (b) bending test with tensile of the base material*

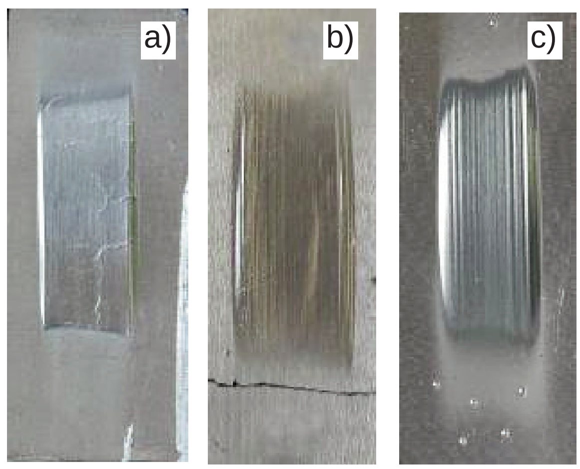

Figure 15. *A view of the specimen's surface after the abrasive wear test (a) weld face, (b) abrasion-resistant layer, (c) steel Hardox400*

Table 9. *Test results related to the abrasive wear resistance of the welded joints made of the abrasion resistant plates (according to ASTM G65 – 04)*
* - relative resistance to abrasive wear compared to the abrasive wear resistance of steel Hardox400, thickness: 6 mm

Specimen designation	Spec. no.	Weight of specimen before the test [g]	Weight of specimen after the test [g]	Mass loss, [g]	Mean mass loss, [g]	Mean volume loss, [mm^3]	Relative abrasive wear resistance *
Steel Hardox	P0-1	62.1029	61.032	1.0709	1.0691	138.8705	1
	P0-2	62.5591	61.4918	1.0673			
Abrasion-resistant plate	P1-1	109.7678	109.616	0.1518	0.1534	20.9849	7
	P1-2	110.0687	109.9137	0.155			
Nanocrystalline weld	P2-1	102.9477	102.8393	0.1084	0.1113	12.6765	11
	P2-1	101.7964	101.6821	0.1143			

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4. Conclusion

The described research regarding the analysis of the properties of welded joints using a Fe-Cr-Nb-B type nanocrystalline-structured filler material showed the possibility of obtaining elements that meet strength requirements and adequate abrasive wear resistance. The study showed that the face weld contains the crystallites at 20 nm, which classifies this material as a nanocrystalline material.

In the matrix of this layer, numerous precipitations of chromium carbides and niobium carbides can be observed, which ensures high hardness up to 70 HRC on the surface and 11 times higher resistance to metal-mineral abrasive use compared to Hardox400 steel reference.

The austenitic filler material used in this process is characterized by high plasticity and is a kind of buffer between the non-alloy steel layer and the abrasion resistant layer, ensuring the reduction of crack propagation to the base material. The implementation of the filling layer using the MAG method ensures an increase in welding process efficiency, with an appropriate level of strength properties. The tests of mechanical properties showed that the welded joints have a tensile strength of about 370 MPa, and the rupture occurred outside the weld area.

Due to the construction of the wear plate, the tensile strength should be determined for the cross-section reduced by the thickness of the wear-resistant layer. Satisfactory bending angles were achieved in the bending test. To sum up, it should be stated that the used Fe-Cr-Nb-B type filler material with a nanocrystalline coated electrode structure to make a weld joint of a wear layer meets the requirements for abrasive wear resistance and ensures weld and HAZ hardness at the hardness level of wear plates.

To weld root beads, it is recommended to use an austenitic filler characterized by very good plastic properties, limiting the degree of mixing the weld with the abrasion resistant material. To make the filling layer, it is recommended to use the MAG welding method with low-alloy filler material, which allows increasing the efficiency of the welding process. Such a selection of welding methods and types of filler materials ensures obtaining appropriate operational properties of the manufactured elements.

Acknowledgments

This work was funded through the following research grant: „ Rector's pro-quality grant", 2019 , Silesian University of Technology in Gliwice.

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PROCENA KVALITETA ZAVARENOG SPOJA OD PLOČA OTPORNIH NA ABRAZIONO HABANJE

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Apstrakt

U ovom članku se predstavlja analiza strukture i osobina zavarenih spojeva od ploča otpornih na abraziono habanje koji imaju strukturu hromiranog livenog gvožđa i zavareni su metalno punjenim žicama, a koji se upotrebljavaju da bi obezbedili visoku otpornost na abraziono habanje površinskog sloja kao i dobre mehaničke osobine osnovnog materijala. Lice zavarenog spoja napravljeno je MMA (Ručno elektrolučno zavarivanje) metodom zavarivanja i metalno punjenim žicama sa nanokristalnom Fe-Cr-Nb-B ispunom. Koreni zavar spoja je zavaren austentnim ispunom, dok je zavar ispune zavaren korišćenjem MAG metode i niskolegiranom ispunom. Spojevi su izloženi nerazarajućim metodama ispitivanja (vizuelno ispitivanje i ispitivanje penetrantima) kao i testovima ispitivanja mehaničkih osobina. Istraživanje je uključivalo i makroskopska i mikroskopska metalografska ispitivanja, određivanje veličine zrna korišćenjem Xpert PRO X-ray difraktometra, i EDS analizu hemijskog sastava taloga. Procena radnih karakteristika zavarenih spojeva zasnovana je na merenjima tvrdoće, statičkim ispitivanjima istezanja i savijanja, kao i identifikovanjem otpornosti na abraziono habanje metala-minerala koje je urađeno u skladu sa ASTM G65 – 04 standardima. Rezultati ispitivanja otpornosti na abraziono habanje odnosile su se na čelik HARDOX 400 koji je bio referentni uzorak. Iz rezultata ispitivanja zaključeno je da korišćeni materijal za ispunu može da obezbedi odgovarajuće radne karakteristike zavarenih ploča otpornih na abraziono habanje.

Ključne reči: *Abrazija; Ploče otporne na abraziono habanje; Zavarivanje; Nanokristalna metalna ispuna*

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