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The Analysis of the Abrasive and Erosive Wear Resistance of Abrasion-Resistant Sheets

Abstract: The article presents results of tests concerning the assessment of the abrasive and erosive wear of abrasion-resistant plates fabricated by Polish and overseas manufacturers. Materials used in the tests, i.e. the Castolin CDP® 1001, CDP® 4666 and CeraMetal® HCCr plates were made using the automated arc welding technology. Reference materials used in the tests were both Polish and overseas abrasion-resistant plates. The analysis of the results of hardness tests performed in accordance with PN-EN ISO 6508-1:2016 as well as of the results of abrasive and erosive wear tests performed in accordance with ASTM G65-00 and ASTM G76-04 enabled the indication of materials characterised by the most favourable functional properties enabling operation under conditions of intense metal-mineral abrasive wear.

Keywords: abrasion, tribology, overlays, FCAW, erosion, wear resistance

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Introduction

The development of innovative chemical compositions of engineering materials characterised by a long service life under harsh operation conditions as well as the development of manufacturing technologies enabling the obtainment of such materials pose an important economic issue. The market offers a wide range of materials resistant to various types of wear including erosion, abrasion or corrosion, often interrelated under certain environmental and load-related conditions, to which a given element is exposed. The selection of an appropriate material satisfying assumed functional requirements entails thorough analysis aimed to protect a given structure against wear in its work environment. Materials characterised by appropriate abrasive wear resistance and other functional properties are obtained in a complicated technological process. The primary application areas of abrasion-resistant sheets include the extractive and power engineering industries as well as the production of cement, where such sheets are used to make chutes, concrete mixers or various rotors. Related tests concerning the wear of machinery elements revealed that abrasive wear constitutes approximately 50% of defects. As can be seen, the reduction of abrasive wear through an increase in hardness and strength/resistance leads to significant material and, consequently, financial savings.

Materials presently applied in environments characterised by high abrasive and erosive wear include abrasion-resistant steels Hardox®,

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Hardstal®, Miilux®, Raex®, Xar® and Htk®. The high resistance-related properties of the above-named steels result from the combination of complicated heat treatment and strictly controlled chemical composition. As a result, it is possible to obtain materials characterised by required hardness as well as abrasive and erosive wear resistance, yet also by relatively high prices.

The market offers a wide range of alternatives to the above-named steels, in the form of abrasion-resistant sheets/plates, usually made using flux-cored arc surfacing, plasma powder transferred arc surfacing or manual metal arc surfacing. Abrasion-resistant sheets provide necessary protection to elements exposed to significant abrasive wear and erosion. The service life of such sheets is between ten and twenty times longer than that of conventional unalloyed steels. Depending on operating conditions of related elements, the base materials used in the aforesaid technologies include various steel grades, usually unalloyed structural steels such as S235JR and S355JR+N. The surface to be directly exposed to abrasive wear is made using the surfacing process and materials based on iron with carbides of chromium, tungsten, vanadium, niobium and borides. Depending on their chemical composition, deposited layers can contain various structures from ferritic, through pearlitic, martensitic to austenitic. The thickness of a layer obtained using the above-named process is restricted within the range of 50% to 80% of the base material thickness, with the primary emphasis given to the lowest possible dilution (of the base material in the overlay weld).

As a result, it is possible to obtain a layer characterised by required hardness, strength and abrasive wear resistance, thus extending the effective service life of machinery elements exposed to tribological wear. The adjustment of appropriate chemical composition, structure and carbide precipitates, the hardness of which is restricted within the range of 1500 HV to 3000 HV, enables the obtainment of abrasive wear resistance between ten and twenty times higher than that typical of standard materials operated under the above-named conditions.

The primary advantage of abrasion-resistant sheets/plates is their usability in the production and repair of machinery elements without compromising the long service life of a given product exposed to erosive and abrasive wear. Abrasion-resistant sheets obtained through surfacing can be subjected to plasma cutting and, next, be formed through bending or rolling aimed to produce elements useable in a given environment. The above-named sheets can be joined using fillet and butt welding, adhesive bonding involving the use of resin-metallic composites or by riveting. Deposited abrasion-resistant sheets significantly reduce material costs and, at the same time, extend the service life of products exposed to tribological wear [1-7].

Individual research

The tests discussed in the article aimed to determine the tribological properties of abrasion-resistant sheets/plates manufactured in Poland and overseas, commonly applied in various industries (Table 1). The tests included the assessment of the abrasive wear resistance and the erosive wear resistance of sheets exposed to high abrasive and erosive wear as well as the comparison of the above-named parameters with related properties of reference materials, i.e. sheets made of overseas abrasion-resistant steel having a nominal hardness of 48 HRC (designated as X1) and Polish steel having a typical hardness of 43 HRC (designated as X2).

Tests of the abrasive wear resistance of the working layer of the abrasion-resistant material

The tests of the metal-mineral type abrasive wear resistance of the working layer of the abrasion-resistant material were performed in accordance with recommendations contained in the Astm G65-00 standard, Procedure A [12]. The test rig used in the tests is presented in Figure 1.

Table 1. Abrasion-resistant materials

Producer and commercial name/designation of the abrasion-resistant material (alloying elements); hardness as declared by the producer	Description
Castolin CDP® 1001 (data restricted by the producer) 58÷60 HRC	The abrasion-resistant sheet made using the arc surfacing technology. The overlay weld is composed of carbide precipitates (1500–2200 HV) bound by the deformable matrix. The application of an innovative solution enabling the control and adjustment of temperature during the manufacturing process limits the dilution (of the base material with the undercoat plate, i.e. steel S235JR+N). As a result, the entire thickness of the overlay weld is characterised by constant and high abrasive wear resistance. The sheet can be used at higher temperature (max. 350°C). In addition, the sheet can be subjected to welding, plasma cutting and formed using moulds [8].
Castolin CDP® 4666 (C, Cr, Nb, B, Fe) 62÷65 HRC	The abrasion-resistant sheet with the arc powder surfaced working layer containing above 50% of chromium (Cr7C3) and additional precipitates of niobium carbide (NbC) and chromium boride (Cr2B). The sheet, characterised by very high abrasive wear resistance and erosive wear resistance, is used primarily to protect machinery elements against erosive wear and abrasion with mineral materials. The sheet can be used at a temperature of up to 400°C and be exposed to slight impact. The sheet is formed through rolling and bending by means of moulds [8].
CeraMetal® HCCr (C, Cr, Fe) 58-62 HRC	The bimetallic sheet composed of steel S235JR and an overlay weld deposited on the steel. The steel is characterised by high abrasive wear resistance and medium impact load resistance. The overlay weld contains the austenitic structure with a significant amount of chromium carbide (Cr7C3) precipitates (constituting over 50%). The unique properties of the HCCr abrasion-resistant sheet result not only from the significant amount of precipitated carbides, but also from their optimum structural arrangement. Because of the significant content of chromium in the overlay weld, the working layer is characterised by high corrosion resistance. The HCCr is used in blades and mixer components as well as surfaces of pipes, scrapers and crushers [9].
Abrasion-resistant steel X1 (C, Mn, Cr, Ni, Si, Mo) 45÷50 HRC	The sheet made of abrasion-resistant steel, used in the making of elements characterised by high abrasive wear resistance, high guaranteed toughness and mechanical workability as well as high bendability and weldability. The sheet is used in bulldozer blades, chute lining panels, concrete mixer linings and slide plates. The material is steel hardened in cross-section. The minimum core hardness amounts to 90% of the minimum guaranteed surface hardness [10].
Abrasion-resistant steel X2 (C, Mn, Cr, Mo, Si, Ni) 41÷50 HRC	The abrasion-resistant sheet made by a Polish manufacturer. The sheet is characterised by good weldability and a high guaranteed yield point in the as-delivered state. The sheet is used in construction and roadmaking equipment, agricultural equipment (ploughshares, crushers, and spreaders), open load-carrying bodies, ball grinder drums. The sheet is made within the thickness range of 3 m to 80 mm. The sheet is formable through cold bending [11].

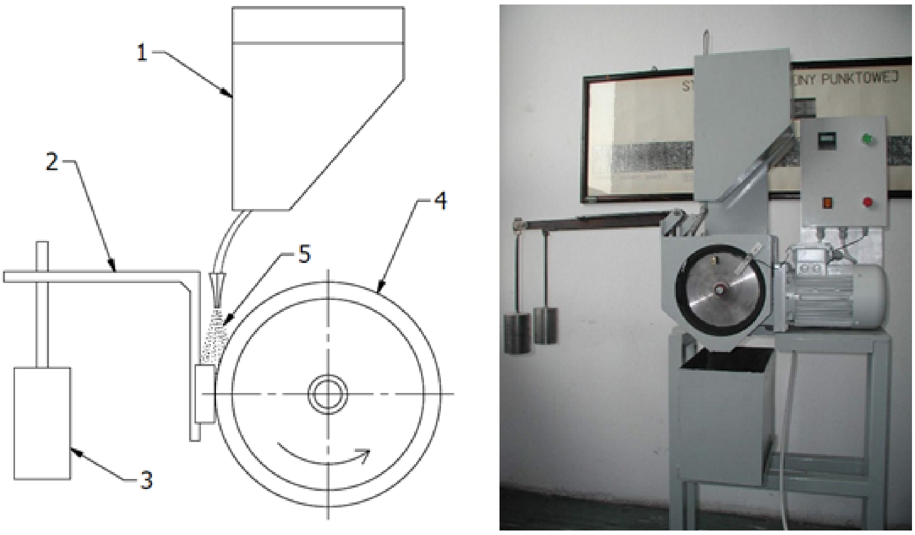


Fig. 1. Test rig used in the metal-mineral type abrasive wear resistance tests performed in accordance with the ASTM G65-00 standard, Procedure A.
1 – container for powder, 2 – specimen fixing grips, 3 – weights,
4 – abrasive wheel, 5 – abrasive

The abrasive wear resistance tests involved cutting specimens (75 mm x 25 mm) out of the abrasion-resistant materials. In accordance with the requirements specified in the ASTM G65-00 standard, the abrasive used in the tests was the Ottawa A. F. S. Testing Sand 50-70, the grain of which is presented in Figure 2. During the test, the rubber wheel of the testing machine made 6000 revolutions in relation to each specimen, where the flow of the abrasive amounted to 335 g/min. The force, at which the sheets were pressed against the rubber wheel, amounted to 130 N.

The abrasive wear resistance tests required that each specimen be weighed by means of a laboratory balance before and after the test, at an accuracy of up to 0.0001 g. During the above-named measurements it was necessary to precisely remove sand residue off the surface as it could significantly affect the accuracy of measurements. The density of the working layer of the abrasion-resistant materials used in the tests was identified by measuring the weight of the specimens in air followed by measurement performed in liquid of known properties (Table 2). The measure of abrasive wear resistance in a given test was a mass decrement determined on the basis of the average mass decrement after an abrasive wear resistance test and of the density of a given specimen calculated in accordance with the following dependence (1):

$$\textit{Volumetric mass decrement [mm}^3\textit{]} = \textit{mass decrement [g]} : \textit{density [g/cm}^3\textit{]} \times 1000 \qquad (1)$$

The results obtained in the metal-mineral type abrasive wear resistance tests were compared with the values of the sheets made of abrasion-resistant steel x1 and x2. As a result, it was possible to determine the abrasive wear resistance of individual materials subjected to the tests (Table 3).

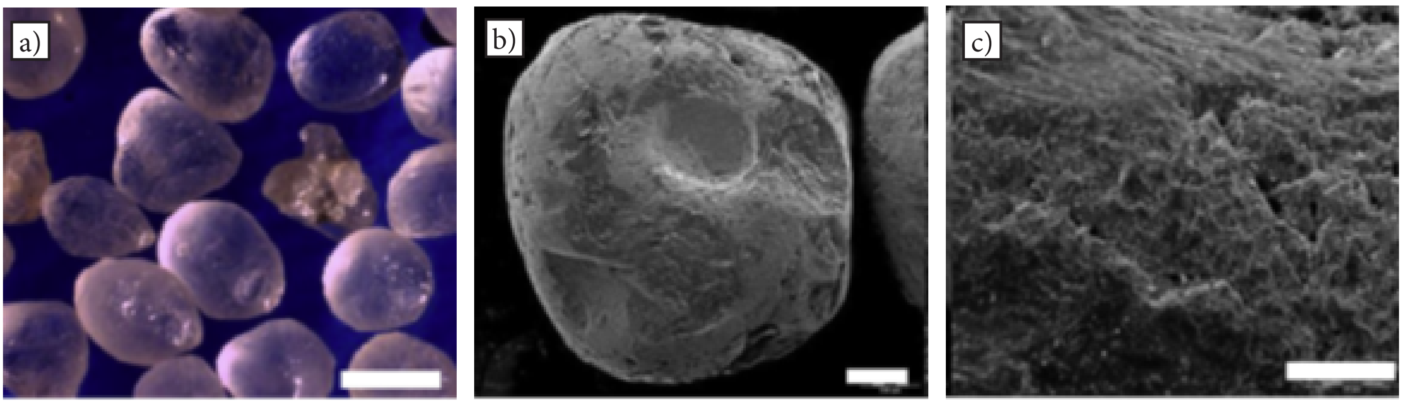


Fig. 2. Grain of Ottawa A. F.S. Testing Sand 50-70 used in the tests of abrasive wear resistance performed in accordance with the ASTM G65-00 standard; procedure A.
a) sand grains, b) one sand grain (SEM), c) surface of one sand grain (SEM) [1]

Table 2. Density of the metal of the abrasion-resistant working layer and of abrasion-resistant steel X1 and X2

Specimen designation	Density [g/cm³]			Average density [g/cm³]
	Specimen number			
	1	2	3	
CDP® 1001	7.3219	7.3297	7.2901	7.3139
CDP® 4666	7.4076	7.3851	7.3768	7.3898
HCCr	7.1804	7.2957	7.3270	7.3756
X2	7.7452	7.7125	7.6959	7.7179
X1	7.7120	7.7423	7.7463	7.7335

Figure 3 presents the working surface of the specimens made of the abrasion-resistant materials after the metal-mineral type abrasive wear resistance test performed in accordance with the ASTM G65-00 standard, Procedure A.

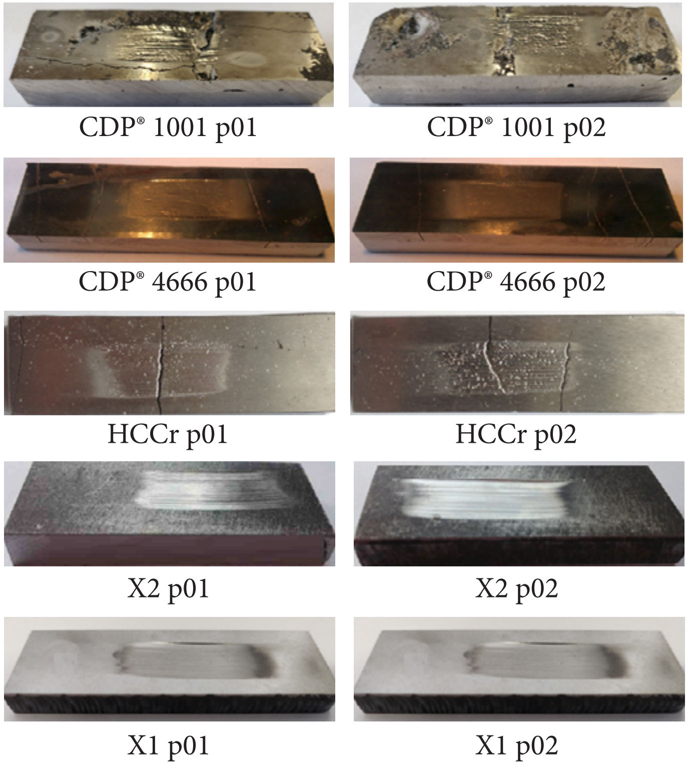


Fig. 3. Working surface of the specimens after the metal-mineral type abrasive wear resistance test performed in accordance with the ASTM G65-00 standard, Procedure A

Rockwell hardness tests concerning the working layer of the abrasion-resistant material

Hardness tests concerning the surface of the abrasion-resistant layers and the reference material involved the Rockwell method in scale C in accordance with the PN-EN ISO 6508-1:2014-12 standard. The measurements were performed using a Rockwell Hardness Tester SHR-1500E (Sunpoc). Before the measurement, the surfaces of the materials were subjected to grinding. The tests involved the performance of five

Table 3. Test results concerning the abrasive wear resistance of the abrasion-resistant materials compared with the abrasive wear resistance of abrasion-resistant steel X1 and X2

Results of abrasive wear resistance test									
Specimen designation	Spec. no.	Weight before test [g]	Weight after test [g]	Mass decrement [g]	Aver. mass decr. [g]	Layer density [g/cm3]	Volume decrement [mm3]	Abrasive wear resistance in relation to the material	
								X1	X2
CDP® 1001	p1	173.3469	173.1466	0.2003	0.1635	7.3139	22.3546	3.19	3.99
	p2	178.7772	178.6505	0.1267					
CDP® 4666	p1	117.5858	117.4788	0.1070	0.0860	7.3898	11.6377	6.12	7.67
	p2	116.2792	116.2142	0.0650					
HCCr	p1	136.7594	136.6901	0.0693	0.0727	7.3756	9.8568	7.23	9.05
	p2	135.7676	135.6915	0.0761					
X2	p1	128.0755	127.3973	0.6782	0.6865	7.6955	89.2079	0.80	1
	p2	115.9037	115.2090	0.6947					
X1	p1	112.5841	111.7872	0.7969	0.5508	7.7335	71.2226	1	1.25
	p2	113.1103	112.8057	0.3046					
Note: Force exerted against the specimens during the test amounted to 130 [N]									

measurements along one line located outside the area subjected to abrasive wear resistance tests (Fig. 4). The test results along with their average values are presented in Figure 4.

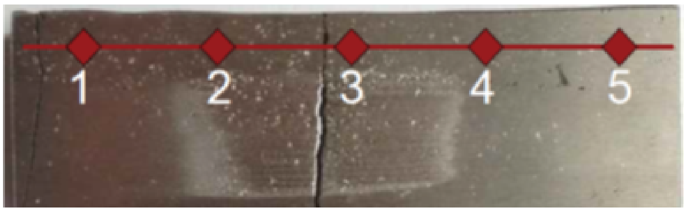


Fig. 4. Schematic arrangement of the measurement points on the surface of the working layer of the abrasion-resistant material

Erosive wear resistance tests

The erosive wear resistance tests of the materials were performed following the recommendations specified in the ASTM G 76-04 standard [13], using a testing station presented in Figure 5. The erosive wear resistance tests involved the emission of solid abrasive particles under gas pressure making particles strike the specimen surface. When striking the surface at a given angle, the erodent was responsible for mass decrement, i.e. the value measured during the test. The erodent used in the tests was the Al_2O_3 powder, the single grain size of which amounted to 50 μm. The erodent flow rate during the test amounted to 2±0.5 g/min, where the velocity of erodent leaving the nozzle (and directed towards the specimen) amounted to 70±2 m/s. Each specimen was tested for approximately 10 minutes, where the distance between the nozzle emitting the erodent and the test element amounted to 10 mm. The tests were performed for three values of erodent angle of incidence, i.e. 90°, 60° and 30°. After each test, the specimens were thoroughly cleaned and weighed using a laboratory balance having an accuracy of 0.0001 g. For each specimen, a volumetric mass decrement was calculated in accordance with dependence (2) and erosive wear resistance in accordance with the ASTM G76-04 standard – formula (3). The final stage included the calculation of relative erosive wear resistance and involved the use of the sheets made of abrasion-resistant steels X1 and X2 as reference materials.

$$\textit{Volumetric mass decrement } [mm^3] = \frac{\textit{Mass decrement } [g]}{\textit{Density } [g/cm^3] \; x1000} \tag{2}$$

$$\textit{Erosive wear resistance } [mm^3/g] = \frac{\textit{Erision rate } [g/min]}{\textit{Erodent flow } [g/min]} / \textit{Material density } [g/cm^3] \tag{3}$$

Table 4. Results of Rockwell method-based hardness measurements concerning the working layer of the abrasion-resistant materials

Hardness of the abrasion-resistant layer, [HRC]								
Specimen designation and number		Measurement point number						
		1	2	3	4	5	Average value	
CDP® 1001	p01	57.1	57.9	58.2	58.2	58.0	57.8	57.6
	p02	57.5	58.0	58.2	56.0	57.5	57.4	
CDP® 4666	p01	62.8	63.9	60.9	61.2	60.3	61.8	62.1
	p02	62.8	61.6	61.1	62.1	64.5	62.4	
HCCr	p01	60.7	60.1	60.2	60.3	60.7	60.4	60.3
	p02	60.8	59.8	60.7	59.9	59.7	60.2	
X2	p01	42.0	43.0	42.5	42.5	42.0	42.4	42.3
	p02	42.0	42.0	42.0	42.5	42.5	42.2	
X1	p01	49.0	49.5	49.5	49.5	50.0	49.5	49.5
	p02	49.5	49.5	50.0	49.0	49.5	49.5	

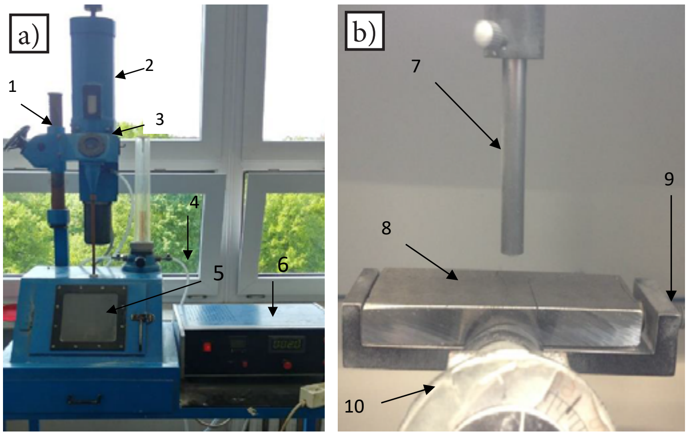


Fig. 5. Station for erosive wear resistance tests, a) main view: 1 – micrometric screw for the adjustment of the distance between the specimen and the erode-emitting nozzle, 2 – container for erodent, 3 – powder feeding system, 4 – compressed air feeding conduit, 5 – working chamber, 6 – control system, b) working chamber inside: 7 – sintered carbide erodent nozzle, 8 – specimen, 9 – fixing of the specimen, 10 – goniometer

Table 5. Results of erosive wear resistance tests concerning the abrasion-resistant materials compared with abrasion-resistant steel X1 and X2

Sheet	**Mass decrement [mg]**	**Density [g/cm³]**	**Volume decrement [mm³]**	**Erosion rate [mg/min]**	**Erosive wear resistance according to ASTM G76 [0.001mm³/g]**	**Erosive wear resistance in relation to steel**	
						X1	**X2**
Erodent angle of incidence - 90°							
CDP® 1001	3.1	7.3139	0.42	0.31	21.19	1.13	1.36
CDP® 4666	2.0	7.3898	0.27	0.20	13.53	0.72	0.87
HCCr	3.8	7.3756	0.52	0.38	25.76	1.37	1.66
X2	2.4	7.7179	0.31	0.24	15.55	0.83	1
X1	2.9	7.7335	0.37	0.29	18.75	1	1.21
Erodent angle of incidence – 60°							
CDP® 1001	2.0	7.3139	0.27	0.20	13.67	0.88	0.92
CDP® 4666	3.5	7.3898	0.47	0.35	23.68	1.53	1.59
HCCr	3.6	7.3756	0.49	0.36	24.40	1.57	1.64
X2	2.3	7.7179	0.30	0.23	14.9	0.96	1
X1	2.4	7.7335	0.31	0.24	15.52	1	1.04
Erodent angle of incidence – 30°							
CDP® 1001	2.2	7.3139	0.30	0.22	15.04	0.89	0.97
CDP® 4666	2.3	7.3898	0.31	0.23	15.56	0.93	1
HCCr	1.8	7.3756	0.24	0.18	12.20	0.73	0.78
X2	2.4	7.7179	0.31	0.24	15.55	0.93	1
X1	2.6	7.7335	0.34	0.26	16.81	1	1.08

Metallographic tests

Microscopic metallographic tests, performed in the transverse plane of the specimens, aimed to identify the structure and types of precipitates in the working layers of the abrasion-resistant materials. Tables 6 and 7 present the microstructure of the individual test materials and the reference materials, i.e. sheets made of abrasion-resistant steels X1 and X2.

Abrasion-resistant steel x1 is martensitic steel characterised by a tensile strength of 1400 MPa; its structure is obtained from the normalised state through hardening in water followed by tempering. In its initial state, the structure is composed of ferrite and pearlite grains with fine-lamellar cementite. Hardening in water and tempering, the temperature of which depends on the thickness of a given sheet, lead to the formation of tempered martensite structures in the material. In terms of its chemical composition and mechanical properties, abrasion-resistant steel X2 is similar to abrasion-resistant steel X1. In the as-received state, the structure of the steel is composed of tempered martensite. The guaranteed tensile strength of the steel amounts to 1100 MPa.

The microstructure of the CDP® 1001 abrasion-resistant sheet is composed of very hard carbides regularly and densely arranged in the metallic and plastic matrix. Because of the fact that the dilution is low, the properties of the abrasion-resistant layer are maintained across its entire thickness.

Table 6. Microstructure of the sheets made of the abrasion-resistant steels

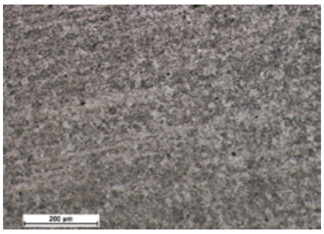
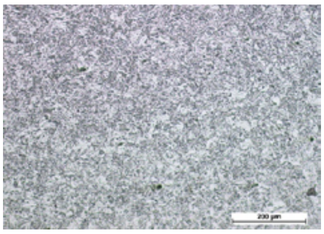
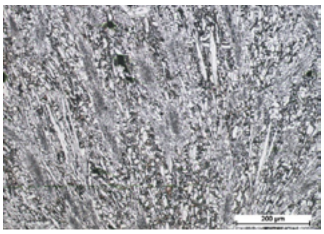
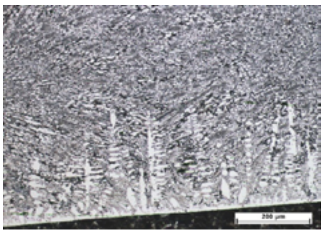
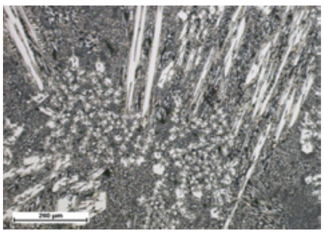
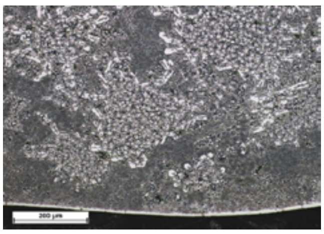
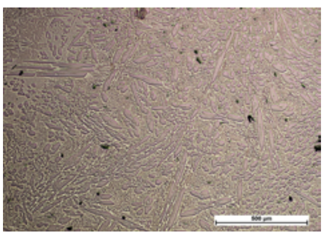
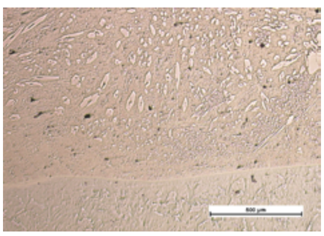
Abrasion-resistant steel X1	**Abrasion-resistant steel X2**
	

Table 7. Microstructure of deposited abrasion-resistant layers

Overlay weld	**Fusion line and base material**
CDP® 1001	
	
CDP® 4666	
	
HCCr	
	

Another abrasion-resistant layer, i.e. the CDP® 4666 sheet is an iron-based hypereutectoid alloy characterised by a high chromium content. The structure of the alloy is composed of a significant amount of Cr_7C_3 chromium carbides (constituting more than 50%) with additional precipitates of NbC niobium carbides and Cr_2B chromium borides located in the plastic matrix. The HCCr material contains the austenitic structure with a significant amount to Cr_7C_3 chromium carbide precipitates, providing the appropriate hardness of the working layer exposed to abrasion wear conditions. Because of the high content of chromium, the layer is characterised by high corrosion resistance.

Summary

The analysis of the test results revealed that the highest metal-mineral type abrasive wear resistance was that of the bimetallic HCCr plate with the FCAW overlay weld containing the austenitic structure with Cr_7C_3 precipitates (constituting more than 50%). In comparison with the reference material, i.e. the sheet made of abrasion resistant steel X1 (Fig. 6a), the abrasive wear resistance of material HCCr was over 7 times higher. Equally high parameters concerning abrasive wear resistance were those of sheet CDP® 4666, containing precipitates in the form of chromium carbides, niobium carbides and chromium borides. The abrasive wear resistance of the above-named material was more than 6 times higher than that of abrasion-resistant steel X1. The last of the materials to be tested, i.e. the CDP® 1001 sheet made using the powder surfacing technology, containing carbide precipitates and characterised by a hardness of up to do 2200HV was 4 time more resistant to abrasive wear than the sheet made of abrasion-resistant steel X2. The greatest difference was observed when comparing

HCCr with abrasion-resistant steel X2, where metal-mineral type abrasive wear resistance was 9 times higher (Fig. 6b).

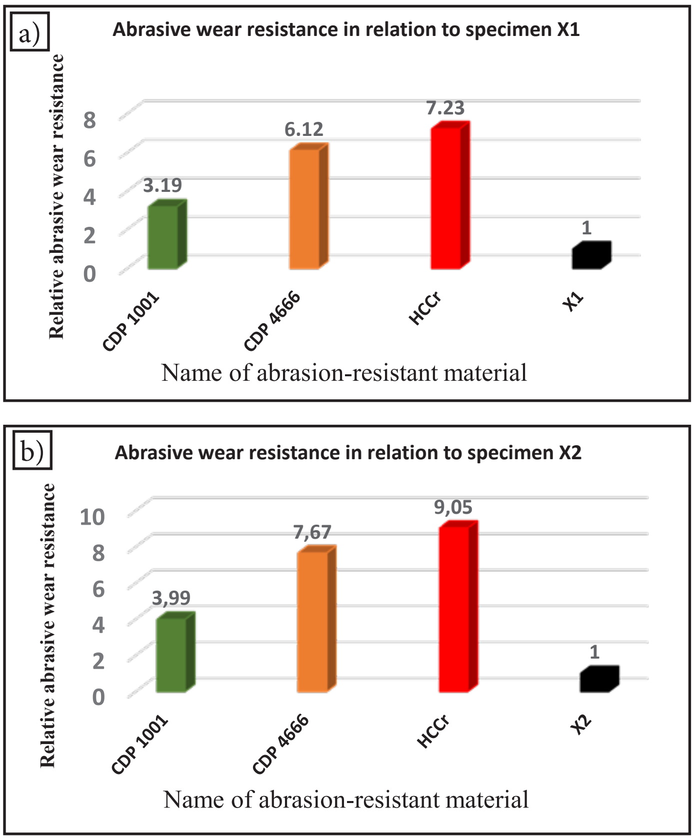


Fig. 6. Metal-mineral type abrasive wear resistance of various abrasion-resistant materials, determined in accordance with the ASTM G65-00 standard in relation to the abrasive wear resistance of abrasion-resistant steels X1 and X2

The highest hardness was that of the CDP® 4666 sheet, the average hardness of which amounted to approximately 62 HRC. The HCCr abrasion-resistant material containing chromium carbides (constituting over 50%) and the CDP® 1001 sheet were characterised by similar hardness values amounting to 60 HRC and 58 HRC respectively. The analysis of the obtained data revealed the existence of the direct correlation between the metal-mineral type abrasive wear resistance and the hardness of a given material.

The tests of erosive wear resistance revealed that in relation to an erodent angle of incidence of 90° and that of 60°, the most favourable properties were those of the HCCr abrasion-resistant sheet. In turn, where the angle of abrasive emission was changed to 30°, the erosive wear

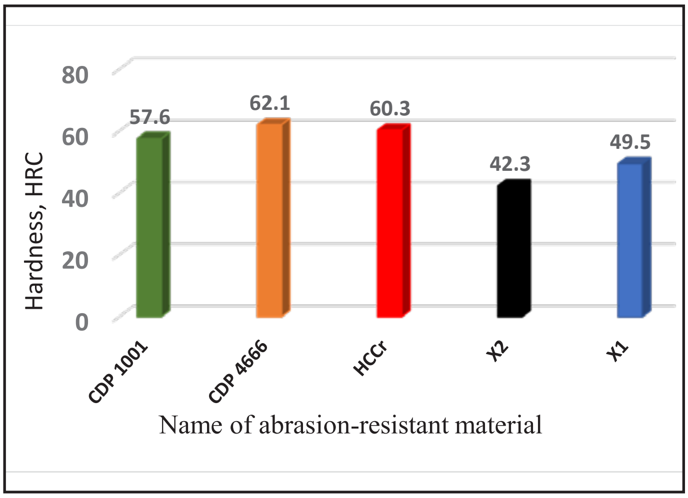


Fig. 7. Average hardness of the surfaces of the working layers of abrasion-resistant materials, determined in accordance with the PN-EN ISO 6508-1:2016 standard

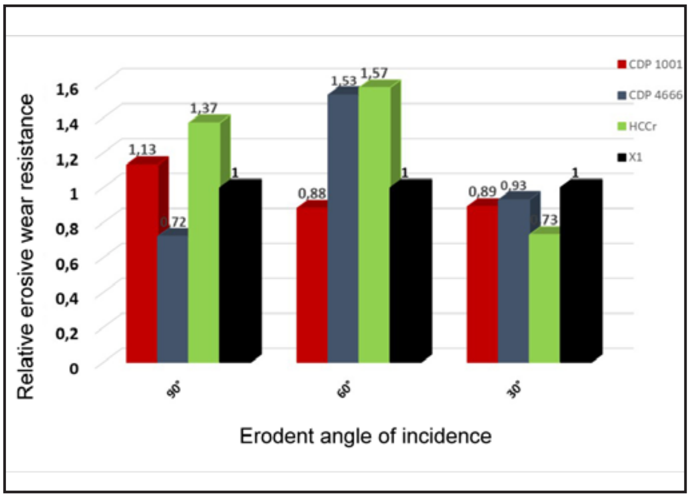


Fig. 8. Erosive wear resistance of the test abrasion -resistant materials, determined in accordance with the ASTM G76-02 standard in relation to abrasion-resistant steel X1 and various erodent angles of incidence

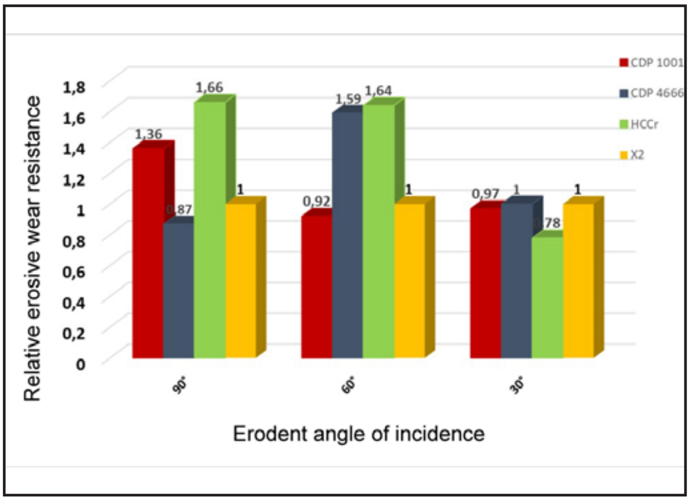


Fig. 9. Erosive wear resistance of the test abrasion-resistant materials, determined in accordance with the ASTM G76-02 standard in relation to abrasion-resistant steel X2 and various erodent angles of incidence

resistance of the above-named abrasion-resistant material was the lowest (Fig. 8 and Fig. 9). The reference materials, i.e. the sheets made of abrasion-resistant steels x1 and x2, were characterised by relatively high erosive wear resistance and slight sensitivity to changes in the erodent angle of incidence (possibly resulting from the homogenous structure of the material obtained during its production).

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