Jacek Górka, Artur Czupryński, Marcin Adamiak, Adam Kopyść

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Evaluation of the properties and structure of nanocrystalline surface layers in relation to selected constructional materials resistant to abrasive wear

Abstract

The present paper is the result of the investigations of the properties and structure of nanocrystalline layers deposited from iron-based nanoalloy on steel S355N substrate by manual metal arc welding method (MMA) compared to selected abrasion-resistant construction materials currently used in industry. The resultant deposit welds were subjected to macro and microscopic metallographic examination. Working properties of obtained nanocrystalline deposits weld compared to currently used materials were evaluated based on the hardness, abrasive wear of metal-to-mineral. The results of deposits weld working properties measurements were compared with property of wear resistant steel HARDOX 400 type used as reference material.

Keywords:
abrasive wear;
nanocrystalline layers;
abrasion plates;
deposit weld

Introduction

The current scientific, technical and economic issue is the problem of wear of machine parts caused by a decrease in working properties of the working surface. In most cases, wear mechanisms are very complex, they include many interrelated factors whose intensity of impact depends on the environment and working conditions. The variety of wear types leads to the specialization of construction materials in order to ensure the highest wear resistance of surface layers under specific operating conditions. One of the types of such materials are wear-resistant plates. The structure of the surface layer and its properties are the decisive elements on the durability of individual machine parts [1÷5]. For several years, there has been a dynamic progress of research on the development of new additional materials enabling the creation of layers characterized by unique properties and structure, different from the properties of the layers previously made. In particular, this applies to such material features as: hardness, resistance to impact loads and low coefficient of friction [5÷7]. The dynamic development of nanostructured materials predicts the increase in their application in welding technologies in the future. The different properties of materials with a nanostructured structure compared to steel mean that the use of nanomaterials in surfacing technologies brings new possibilities. These nanomaterials are single or multi-phase polycrystals characterized by a microstructural grain size of $1 x 10^{-9}$ to $250 x 10^{-9}$ m. At the upper limit of this range, the term „very fine grain size" is used more often (grain size 250÷1000 nm). Nano-crystalline materials are structurally characterized by a high volume share at the grain boundaries, which significantly changes their physical, chemical and mechanical properties in comparison to conventional coarse-grained materials, whose grain size is usually in the range of 10÷300 μm [8÷11]. The previous nanomaterials, which were used for nanostructured layers and coatings, showed many times higher resistance to wear compared to traditional steel materials. However, nanostructured materials do not have wide application in surfacing technologies due to high costs and continuous development of their production technology [12÷14].

Own research

The research was aimed at comparing the properties and structure of the Fe-Cr-Nb-B nanocrystalline surface layers,

dr hab. inż. **Jacek Górka**, prof. PŚl; dr inż. **Artur Czupryński**; dr hab. inż. **Marcin Adamiak**, prof. PŚl; mgr inż. **Adam Kopyść**
– Silesian University of Technology, Poland;

Corresponding author: jacek.gorka@polsl.pl

made by manual arc welding with a coated electrode with a diameter of 3.2 mm, compared to the previously used construction materials resistant to abrasive wear. The reference material in the assessment of resistance to abrasive wear of metal-mineral type was the HARDOX 400 steel. The following materials were tested:

– a nanocrystalline layer made with a coated electrode – NANO (Fe-Cr-Nb-B),
– abrasion resistant plate – ABRECOPLATE,
– abrasion resistant plate – CDP,
– abrasion resistant layer made with coated electrode – ABRADUR 64,
– abrasion resistant layer made with GMA method using cermet wire with 50% share of WC,
– abrasion resistant HARDOX 400 sheet.

The nanocrystalline layer made with Fe-Cr-Nb-B coated electrode

The Fe-Cr-Nb-B nanocrystalline layer (Tab. I) was made by manual arc welding with a 3.2 mm diameter coated electrode on a S355N steel substrate. MMA arc surfacing was carried out with constant current of positive polarity and current intensity of 100 A in the flat position (PA). During surfacing, the electrode was positioned at an angle of 90° to the surface of the surfaced substrate. The surface of the sheet before the surfacing process was ground and pre-heated with a gas burner to a temperature of approx. 80 °C.

According to the manufacturer's data, the deposit weld of Fe-Cr-Nb-B nanocrystalline electrodes in a large volume consists of very hard boron carbide fractions evenly distributed in a half-amorphous iron alloy [15]. The padding weld should have high abrasion resistance and increased resistance to dynamic loads. The electrodes can be used for both constant current and alternating current surfacing. They ensure hardness of 67÷70 HRC.

Abrasion resistant plate – ABRECOPLATE

ABRECOPLATE abrasion resistant materials are produced in the form of: plates (straight, truncated, on special order), bars, buttons (in the shape of a dome, octagonal, protecting screws) [16]. ABRECOPLATE is a layered material composed of chromium-molybdenum white cast iron, metallurgically connected with a underlay plate made of a soft structural steel (Tab. II)

ABRECOPLATE's high abrasion resistance properties are due to the structure of the surface layer. The special heat treatment of cast iron allows to obtain a microstructure consisting of chromium-molybdenum carbides in an almost completely martensitic matrix. The base of these abrasive plates is soft structural steel. The cast iron is connected with the base by soldering with the use of a soft copper-based binder, which ensures a good transfer of stresses. An important advantage of ABRECOPLATE abrasive plates is also the content of abrasive material in relation to the base, which is 3:1.

Table I. Chemical composition and hardness of tested deposit weld

Chemical composition, %							Hardness of deposit weld
C	Cr	B	Nb	Mn	Si	Fe	
1.4	15.2	4.0	3.4	0.4	0.4	rest	68÷70 HRC

Table II. Chemical composition and physical characteristics of ABRECOPLATE

Mass concentration of elements, %					
C	Cr	Mo	Mn	Si	Ni
2.8÷3.6	14.0÷18.0	2.3÷3.5	0.5÷1.5	1.0 max.	5.0 max.
Mechanical properties					
Hardness, HB/HRC	Geat resistance, °C	Creep resistance, °C			
700/64	540	595			

CDP plate

Abrasion resistant plates are manufactured by hardfacing a metal sheet of non-alloy steel, low-alloy or high-alloy steel with gas shielded flux-cored wires or self-shielded flux-cored wires (Tab. III) [15].

The padded layer has a very high abrasion resistance and its standard thickness is 3÷18 mm. Typical dimensions of abrasion resistant plates are: 1000 x 2000 mm, 1500 x 3000 mm and 2000 x 3000 mm. It is possible to cut flat elements of any shape from abrasion resistant plates and shape them by bending and rolling. They are attached to the regenerated substrate with fillet welds, continuous or intermittent, depending on the type of abrasive plate load. The high content of carbon, chromium and niobium allows obtaining a structure similar to that of cast iron with very hard chromium borides, niobium carbides and iron carbides.

Table III. Chemical composition of surface deposit weld

Mass concentration of elements, %							Hardness of deposit weld
C	Cr	B	Nb	Mn	Si	Fe	
5.2	22.0	1.8	7.0	0.4	0.4	rest	57÷62 HRC

Abrasion resistant layer made with ABRADUR 64 coated electrode

The abrasion resistant layer was made by manual surfacing of S335JR steel with a coated electrode DIN 8555:E 10-UM-65-GR with a diameter of 5.0 mm, and current intensity of 270 A. The surfacing process was carried out using a buffer layer made with an ERWS 19-12-3 L coated electrode with a diameter of 3.25 mm, and current intensity of 110 A. The task of the buffer layer was to transfer the stresses between the base material and a hard padding weld. Chemical composition and properties of ABRADUR 64 coated electrode are given in Table IV.

Table IV. Chemical composition and properties of ABRADUR 64 covered electrodes [17]

Mass concentration of elements, %			Hardness, HRC
C	Cr	Nb	
7.0	24.0	7.0	64

Abrasion resistant layer made with GMA method using cermet wire

The abrasion-resistant layer was made by single-layer GMA surfacing of 15HM steel with cermet wire on a nickel matrix with 50% share of tungsten carbide WC [15]. The chemical composition of the surfaced layer after chemical composition analysis is shown in Table V.

Table V. Chemical composition of layer formed by GMA with ceramo-metallic wire layer

The mass concentration of the elements of abrasion resistant layer, %					
Ni	C	Si	Cr	B	WC
Rest	0.4	2.5	3.0	1.5	50

HARDOX 400 steel sheet

Hardox steels are defined as „high-quality abrasion resistant steels". The group of these materials is derived from low-alloy steel for thermal improvement and belongs to a new generation of machinable and weldable structural steels. Materials made of Hardox steel are used where resistance to abrasion is required in the presence of variable loads, e.g. feeders, crushers, sieves, shaft necks, elements of incline haulage, conveyors, blades, gear and chain wheels, dumpers, loaders, trucks, dozers, buckets and screw conveyors. All types of HARDOX steel are delivered in hardened condition (in water), and in the case of relevant required hardness, tempering is also carried out. These steels can be bent, cut, and machined by drilling, milling and turning under strictly defined conditions. HARDOX sheets can be machined using high speed steel (HSS) or tools made of sintered carbides [18]. The chemical composition and properties of HARDOX 400 steel are given in Table VI.

Testing of abrasion resistance of the metal-mineral type according to ASTM G65-00

The tests of resistance to abrasive wear of selected materials were carried out on a test bench, made in accordance with ASTM G65-00. The procedure A was used for the tests, which is the most demanding examination of abrasion resistance. During the test, the sample was mounted in a special holder pressing it to a rubber wheel with a diameter of 228.6 mm. The test sample was pressed against the rubber wheel with a force of 130 N. Abradant, in the form of granular sand, was delivered through the nozzle in place of the sample contact with the rubber wheel. The abradant flow rate was 300÷400 g/min. The wheel rotated in the direction corresponding to the abradant flow, at a speed of 200 rpm and made 6000 revolutions. The samples tested had a dimension of 25x75xg mm. The mass loss was determined using a laboratory scale with a measurement accuracy of 0.0001 g. In order to compare the results of resistance to abrasive wear, a measurement of the density of plates and abrasive layers was carried out. The volume loss of the sample [mm^3], formula (1), table VII, figure 1 were taken as a measure of abrasibility.

$$\text{Volume loss [mm}^3\text{]} = \frac{\text{loss of weight [g]}}{\text{density [g/cm}^3\text{]}} \times 1000 \qquad (1)$$

Table VI. Chemical composition and mechanical properties of HARDOX 400

Mass concentration of elements, %					
C	Mn	Mo	Cr	Si	Ni
0.14÷0.32	1.60	0.25÷0.60	0.30÷1.40	0.70	0.25÷1.50
Mechanical properties					
Hardness, HB	Ultimate tensile strength, MPa	Yield strength, MPa			
370÷430	1250	1000			

Metallographic examinations

The metallographic microscopic examinations allowed to determine the microscopic structure of the examined materials. The observations which were carried out did not show any internal defects in the layers made by welding methods and material defects in the case of HARDOX 400 sheets as well as ABRECOPLATE and CDP plates (Fig. 2).

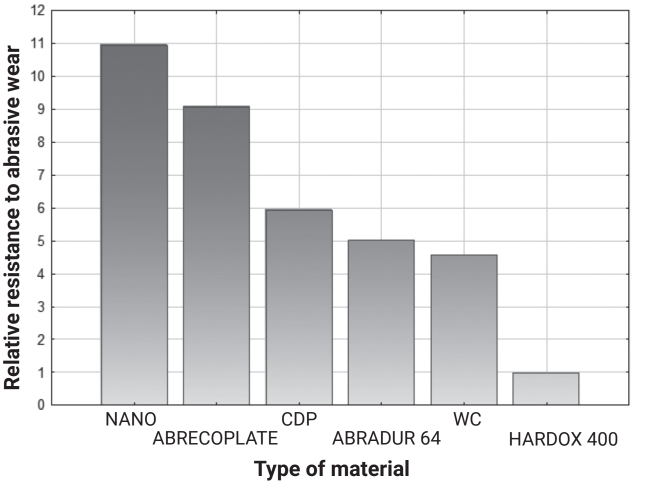

Fig. 1. Comparison of the results of relative abrasive wear resistance of selected construction materials

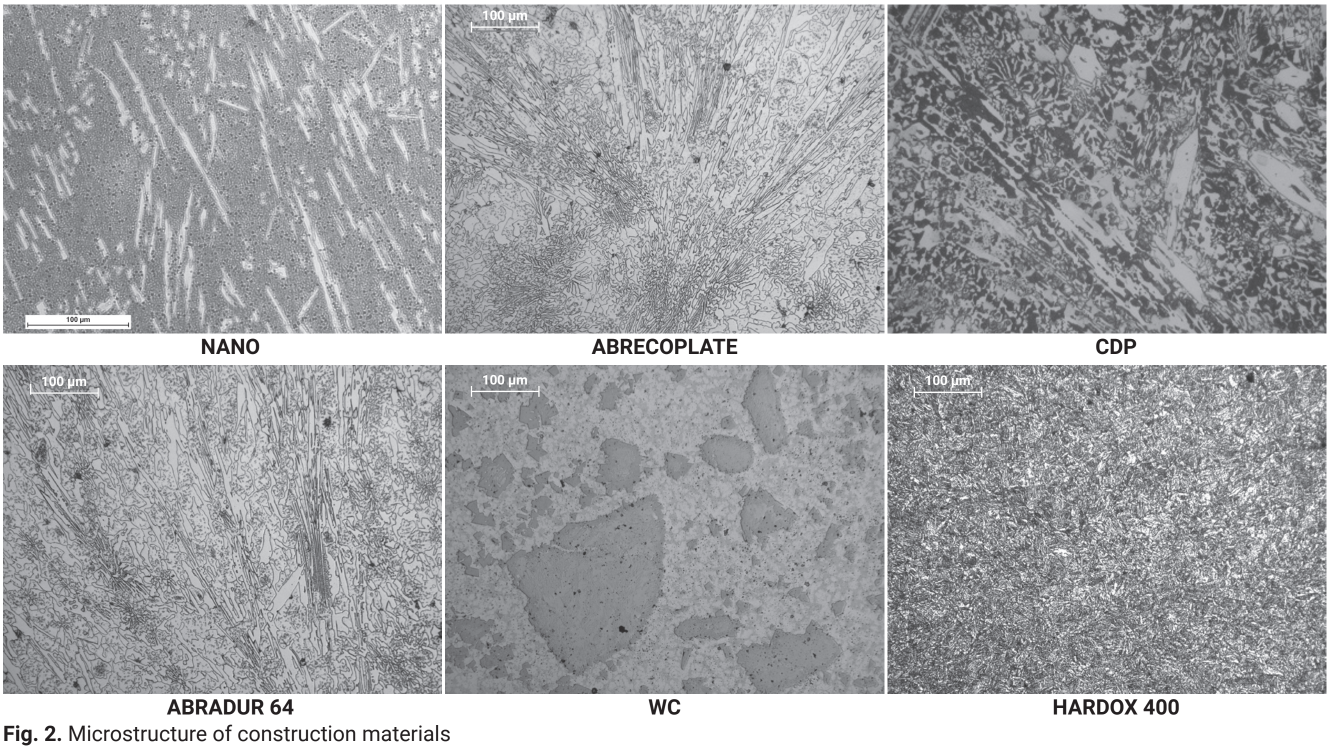

Fig. 2. Microstructure of construction materials

Table VII. ASTM G65-00 abrasion resistance test results

Symbol/density [g/cm³]	Sample number	Weight of the sample before testing [g]	Weight of the sample after testing [g]	Loss of weight [g]	Average weight loss [g]	Average volume loss [mm³]	Relative resistance to abrasive wear*
NANO/8.78	1	102.9477	102.8393	0.1084	0.1113	12.6765	10.95
	2	101.7964	101.6821	0.1143			
ABRECOPLATE/7.5961	1	173.7335	173.6133	0.1202	0.11635	15.3170	9.07
	2	173.6714	173.5589	0.1125			
CDP/7.1724	1	128.6154	128.4378	0.1776	0.1697	23.3881	5.94
	2	128.9438	128.7821	0.1617			
ABRADUR 64/7.1544	1	136.2893	136.0933	0.1960	0.19825	27.7102	5.01
	2	139.6675	139.4670	0.2005			
WC/10.6808	1	179.6026	179.3009	0.3017	0.32360	30.2974	4.58
	2	181.8750	181.5295	0.3455			
HARDOX 400/7.7115	1	62.1029	61.0320	1.0709	1.0691	138.8705	1.00
	2	62.5591	61.4918	1.0673			

Hardness measurement

In order to determine the hardness of the tested materials, hardness measurement was carried out in 5 places on the weld face / sheet surface using Rockwell HRC method, and in 4 places on the padding weld / sheet cross-section using the Vickers method at a load of 1000 g (Fig. 3 and 4). The results of hardness measurements are presented in Table VIII and Figure 5.

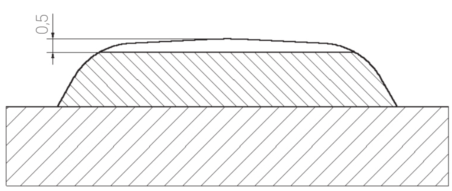

Fig. 3. Preparation for hardness testing

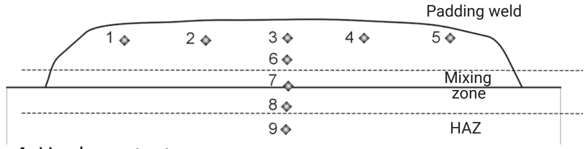

Fig. 4. Hardness test area

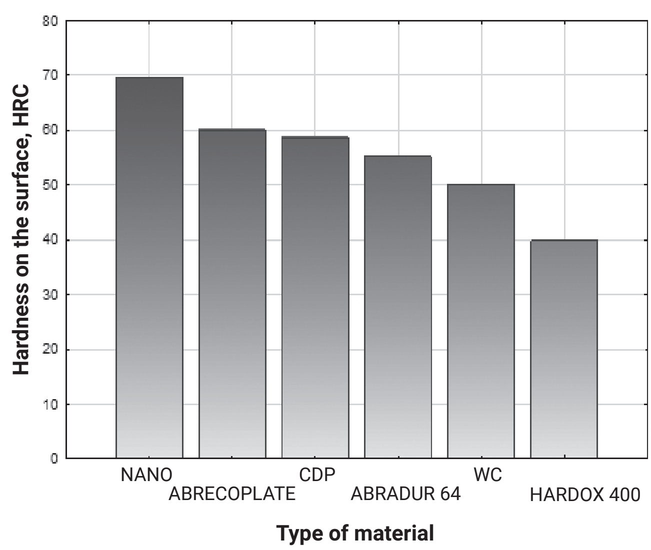

Fig. 5. Average hardness of the surface of tested construction materials

Table VIII. Hardness testing results on the face and cross section of deposit welds and sheets

Material	Hardness HRC						Hardness HV1			
	1	2	3	4	5	Average	6	7	8	9
NANO	69	70	69	71	69	69.60	679	289	179	188
ABRECOPLATE	60	58	61	61	62	60.04	663	154	148	106
CDP	62	59	58	61	58	58.70	643	299	179	182
ABRADUR 64	57	56	57	54	52	55.20	556	174	304	290
WC	54	50	48	51	49	50.04	563	486	180	167
HARDOX 400	41	40	39	40	39	39.80	380	378	377	378

Conclusions

The metallographic examinations of the materials selected for the tests did not show any internal and external defects of the layers made by manual surfacing with coated electrodes and surfacing using GMA method. Measurement of the grain size of the crystallographic nanocrystalline microstructure of Fe-Cr-Nb-B type made using the Xpert PRO X-ray diffractometer from PANalytical showed that the layers were made of crystallites at 20 nm, which classifies these layers as nanocrystalline. The ABRECOPLATE board has a structure of white cast iron with the precipitation of chromium-molybdenum carbides. To connect this plate with a low carbon steel support plate, a soft binder was used on the copper matrix, which perfectly transfers the stresses occurring between the layers. In the case of a CDP, the surface layer structure is a chromium cast iron with a lot of primary carbides. The layer made with coated electrodes ABDADUR 64 has a structure of the eutectic iron with numerous precipitates of niobium and chromium carbides. The use of austenitic steel buffer layer in this case allowed to avoid cracks that could propagate to the substrate material. The layer made by GMA surfacing with a cermet wire is characterized by a nickel matrix with numerous WC carbides. It can be observed that as a result of the thermal cycle, the WC carbides are partially dissolved, which may reduce the abrasion resistance of such layers. HARDOX 400 is characterized by the structure of tempered martenzite. The hardness measurements carried out on the ground face of abrasion resistant layers showed that all materials have a hardness similar to the hardness given by the manufacturers. The highest hardness on the surface is characterized by a nanocrystalline layer, hardness of 70 HRC. The tests of resistance to abrasive wear of the metal-mineral type, according to ASTM G65-00, have shown that the best usable properties are characterized by a layer made of Fe-Cr-Nb-B alloy. The abrasion resistance of the metal-mineral type of this material is 11 times higher than in the case of a typical HARDOX 400 abrasion resistant sheet.

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