Wear Resistance Improvement of Equipment for Production of Building Ceramics by Hardfacing with Flux-Coerd Electrodes based on Fe-Ti-B-C System

doi:10.2478/mape-2020-0023
Date of submission to the Editor: 03/2020
Date of acceptance by the Editor: 06/2020
MAPE 2020, volume 3, issue 1, pp. 263-273

Pavlo Prysyazhnyuk
ORCID ID: 0000-0002-8325-3745

Oleksandr Ivanov
ORCID ID: 0000-0003-4678-7956

Dmytro Lutsak
ORCID ID: 0000-0001-9496-3542

Lyubomyr Lutsak
ORCID ID: 0000-0002-8111-5461
Ivano-Frankivsk National Technical University of Oil and Gas, **Ukraine**

INTRODUCTION

Hardfacing using flux cored arc welding (FCAW) is universal, economically-effective and technologically simple method for restoring and increasing of wear resistance of equipment of various industries, such as production engineering, construction, oil and gas, woodworking, tillage, etc. Such equipment works in aggressive conditions, which are:

- high abrasive wear. Due to contact of equipment (Fig. 1) with hard abrasive particles such as alumina (~ 15…19 GPa), silicon carbide (~ 10…11 GPa), etc. (Ivanov et al., 2018);
- high working speed. Peeling knives (Fig. 1c) works at rotation speed of 175…350 min^{-1}; traditional industrial mixers (Fig. 1a) of abrasive-containing masses processing with a 90…120 min^{-1} rotation speed, and blades of turbo mixers (Fig. 1e) with a 800…1600 min^{-1} rotational speed (Ivanov et al., 2019);
- increased temperatures. Increasing of temperature is result of high working speed and intense friction in contact zone. While peeling the temperature in working zone increase to 200…300°C;
- high impact and specific load. Wet pressing of raw bricks with the use of modern vacuum presses implies a working pressure of compression of 25…28 MPa, whereas this figure for the presses of the previous generation was only 1,8…2,5 MPa; while dry pressing of building ceramics the pressures reaches 30 MPa; production of fuel briquettes involves working pressures in the pressing zone of 20…35 MPa; production of fuel granules

Contact address: pavlo1752010@gmail.com

(pellets) is carried out at a working pressure in the pressing zone of 30…40 MPa (Ivanov et al., 2019).

In combining, above mentioned factors lead to fast wear of such equipment and to the need of increasing their wear resistance.

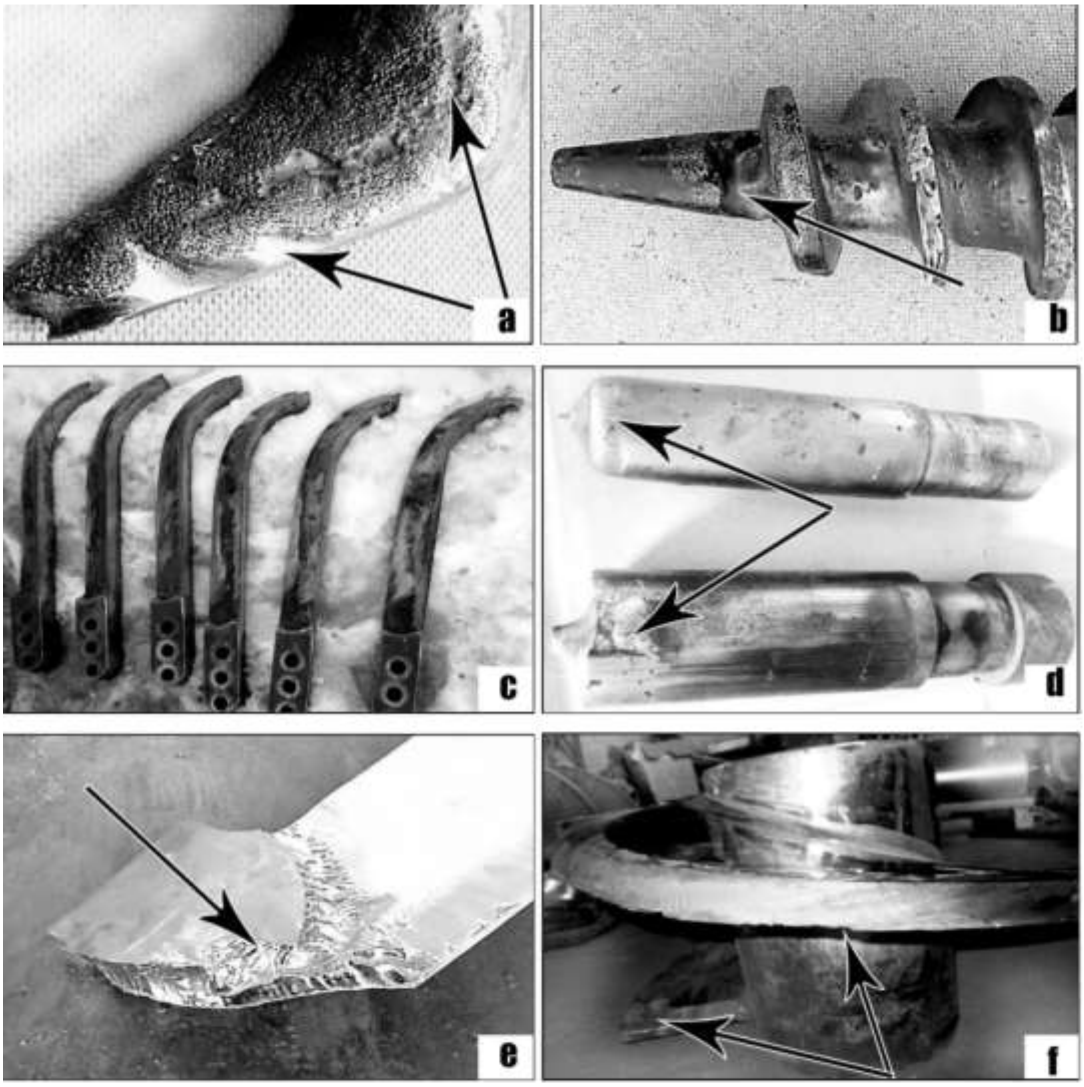

Fig 1 Appearance of worn work surfaces of equipment for processing abrasive materials (arrows indicate the characteristic manifestations of abrasive wear): a – fragment of the blade of the mixer for the manufacture of particleboard; b – auger of a sawdust briquetting press for production of fuel briquettes; c – logs peeling knives; d – punches for sawdust briquetting press for the manufacture of fuel briquettes; e – a fragment of the turbine mixer blades for the manufacture of dry compounds; f – section of a extruder-screw of vacuum press for the manufacture of construction ceramics

Hardfacing with flux cored wires provides productive restoring of such equipment. Among the advantages of FCAW can be highlighted the relative simplicity of the process, which does not require the use of special expensive equipment, as well as the fact that regulating the content of the components of the electrode charge and, accordingly, the chemical ratio of elements, properties of the deposited layer can be predicted in some range. For hardfacing coating that works in conditions of intense abrasion wear such parameters as the microstructure, type of matrix, distribution of carbides, their size, shape and hardness are most important (Wang and Zhang, 2014).

Improving the efficiency of production engineering industries can be achieved in various ways, including the using of cheaper fuel, changing modes of operation, increasing the time between overhauls (TBO) of equipment, using of more wear resistance and more durable materials, etc. Among the considered ways of improving the efficiency it is necessary to allocate two of them - materials which are used for restoring of wear parts and increasing the time between overhauls (TBO) of the equipment as they can be considered interconnected. Materials that are more wear resistant than serial materials, and more resistant than materials of the wear parts can be used for restoring and also for increasing the durability of equipment wear parts, which will increase TBO periods and thus increase the productivity and efficiency of such equipment.

There are few systems that commonly employed for FCAW. Tungsten based hardfacing materials are expensive as well as systems based on Ni, Co and characterized by low resistance to shock load due to its brittles (Badisch and Miller, 2003). Therefore, as alternative to tungsten-based system there the most commonly employed hardfacing materials based on the Fe-Cr-C system due to their high hardness, good corrosion and wear resistance (Sadeghi et al., 2017). However, such materials, based on Fe-Cr-C system, are characterized with low resistance in the conditions of abrasion wear under high working speed, high specific and cyclic loads.

In the works (Wang, Xin-hong et al., 2008., Wang, X. et al., 2008., Jilleh et al., 2013., Liu et al., 2012., Lutsak et al., 2016) scientists are considering using of Ti based systems and Ti addition to the Fe-Cr-C system, which leads to the formation of uniformly dispersed TiC inclusions in the steel matrix.

For alloying the Fe-Ti-C system scientists also uses Nb, V (Qi et al., 2011) and Mo (Zhang et al. 2018). Presence of boron in the system is also advisable, that will provide the formation of borides of and other elements (Pokhmurska and Voitovych, 2015).

In the present investigation the aim was to achieve a hardfacing layer with high volume fraction of refractory compounds dispersed in ductile Fe-based matrix using FCAW wire containing reaction powder mixture of titanium, molybdenum and boron carbide, that can be used for restoring of equipment parts that works in intensive abrasive wear conditions.

METHODOLOGY OF RESEARCH

The FCAW wire was manufactured by placing mixture of powders of initial components into low carbon 08 kp steel (GOST 503-81) with size 0.5 × 20 mm sheath through rolling. The schematic wire cross section is shown in Fig. 2.

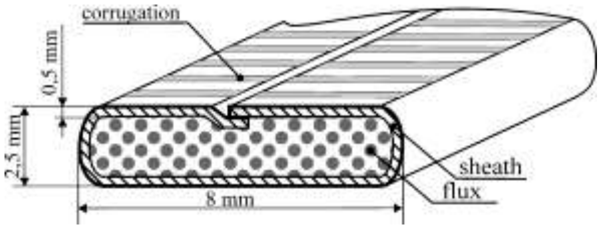

Fig. 2 Schematic drawing of the cross-section of a FCAW wire

As initial components powder of Ti, Mo and B_4C were used. The mass fraction of initial components for each sample shown in Table 1.

Table 1 Nominal composition of samples initial components

Sample No.	Compositions, wt.%		
	B_4C	Ti	Mo
1	27.8	72.2	-
2	20.392	26.4	53.11

The filling coefficient (K_f) of the wire was calculated as the mass ratio between the flux and cored wire according to the formula (1):

$$K_f = \frac{G_{pow}}{G_{el}} \cdot 100\ \% \tag{1}$$

where:
G_{pow} – weight of the initial powder,
G_{el} – weight of filled electrode wire.

Control of the K_f was carried out by weighing not less than three electrodes, with the weighing accuracy 0.01 g.

In present study the filling coefficient was approximately 25%, so the chemical composition of a wire was as shown in Table 2.

Table 2 Nominal compositions of sample wires

Sample no.	Compositions, wt.%			
	B_4C	Ti	Mo	Fe
1	6.95	18.05	-	bal.
2	5.098	6.6	13.278	bal.

To assure the dryness of the initial powders before weighing they were dried in the SNOL-type drying cabinet at 120°C for 1.2 h. Mixing of the powder components was performed on a laboratory gravity drum mixer with an inclined axis of rotation for 1 h. After mixing the mixture was additional dried at 120°C for 0.5 h to prevent influence of air humidity on bulk properties. Before welding electrode wire was cut into 420 mm length electrodes.

The hardfacing was carried out on 3 sp steel (GOST 380-2005) substrate by manual FCAW under direct current with a reverse polarity using VDU-506 rectifier. The welding parameters were as follows: welding current 160-180 A, arc voltage 30-32 V. Cooling was carried out on air at 20°C.

Microstructure was observed with a scanning electron microscopy (SEM) using ZEISS EVO 40XVP electrone microscope. The hardness was measured by means of the average measurements taken from the top surface of the hardfacing layers by Rockwell method, scale "A".

The wear testing with fixed abrasive was carried out without lubrication at room temperature using a wear tester machine, as presented in Fig. 3. The ring material of the wear couple was 64CF46L7V (GOST 52781-2007). The load in the contact area was of 0.1 kN, a sliding speed of 5 m/s and a sliding distance of 600 m. The test specimens were machined as cylinders with radius 10 mm.

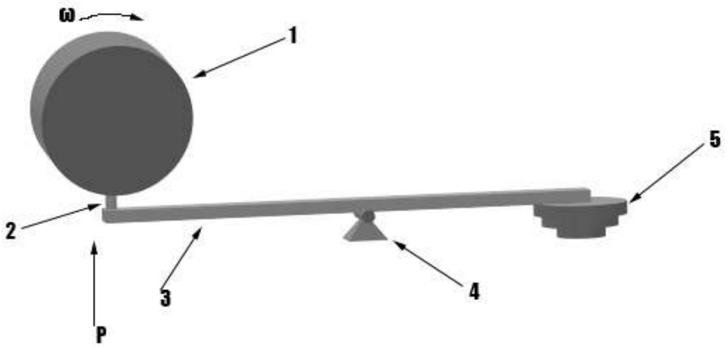

Fig. 3 A schematic diagram of wear testing
1 – abrasive wheel; 2 – sample; 3 –support; 4 – lever; 5 – weight

RESULTS

As shown in Fig. 4, microstructure of sample 1 consist of three phases, different in colors.

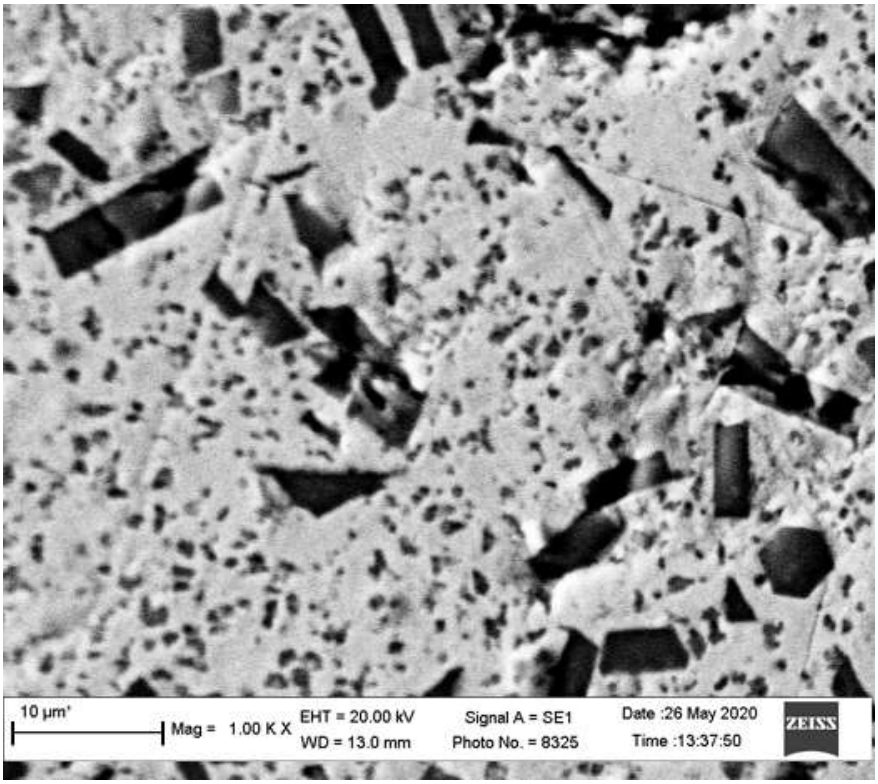

Fig. 4 SEM analysis of the microstructure of FCAW coating of sample 1

The dark phase represented by hexagonal-shaped and uniformly distributed particles with high content of boron and titanium, with size of 8-10 µm. This phase can be matched as TiB_2. The gray phase generally enriched with Ti and C and can be identified as titanium monocarbide (TiC). The bright Fe-rich phase coexists with TiB_2 and TiC in form of a layer surrounding TiB_2 particles and matrix of rod-like eutectic can be matched as ferrite.
As shown in Fig. 5 the addition Mo in equimolar ratio Me/Ti to the Ti-B_4C system significantly affects the peculiarities of structure formation mainly due to the appearance of new phases and significantly grain refinement of MeB_2 phase. After Mo addition Fig. 5 the mean grain size of MeB_2 decreases in approximately two times with remaining of hexagonal grain shape, however MC-based phase does not undergo significant changes in size and shape. Also, the microstructure of sample 2 is significantly different from microstructure of coating received by laser cladding that presented in work (Zhang et al. 2018). The difference is the presence of fine hexagonal-shaped grains, and can be result of effect of "*in-situ*" synthesis reaction during FCAW contains of powders of pure metal and their combinations as initial reaction mixture for electrodes.

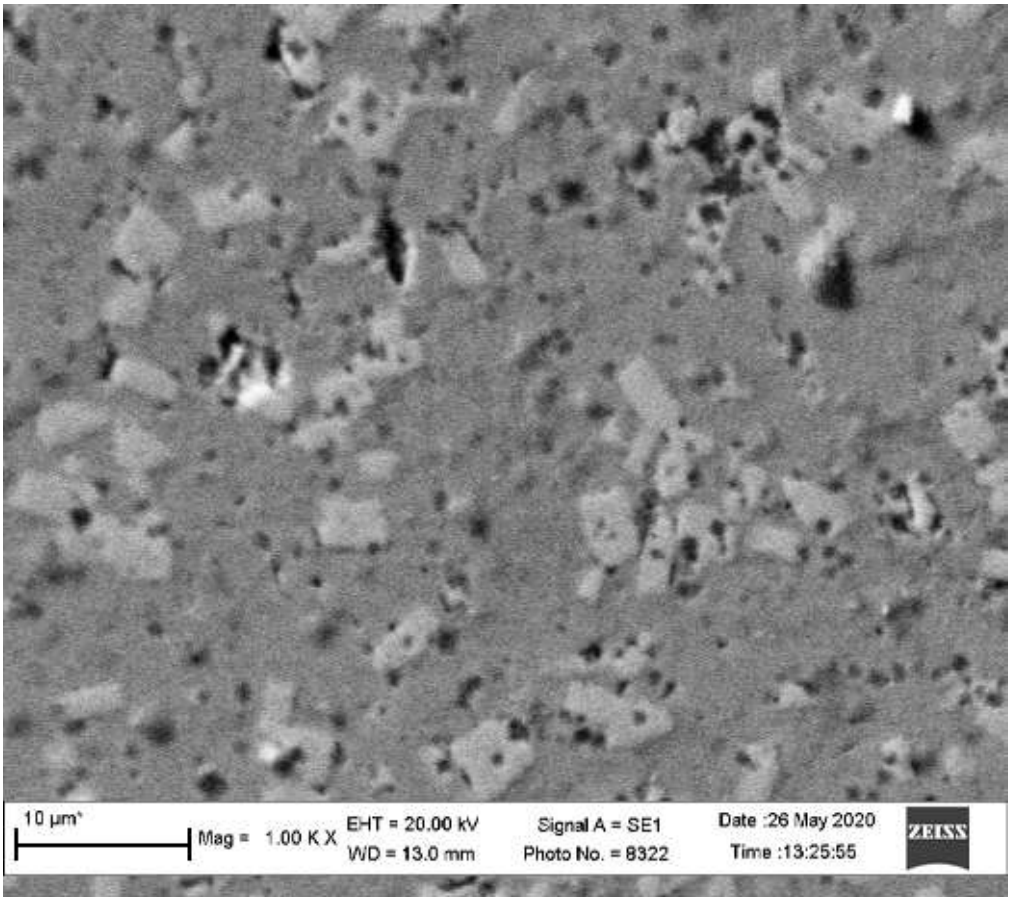

Fig. 5 SEM analysis of the microstructure of FCAW coating of sample 2

Fig. 6 shows results of abrasive wear tests and hardness measurement of tested samples and some modern hardfacing materials.

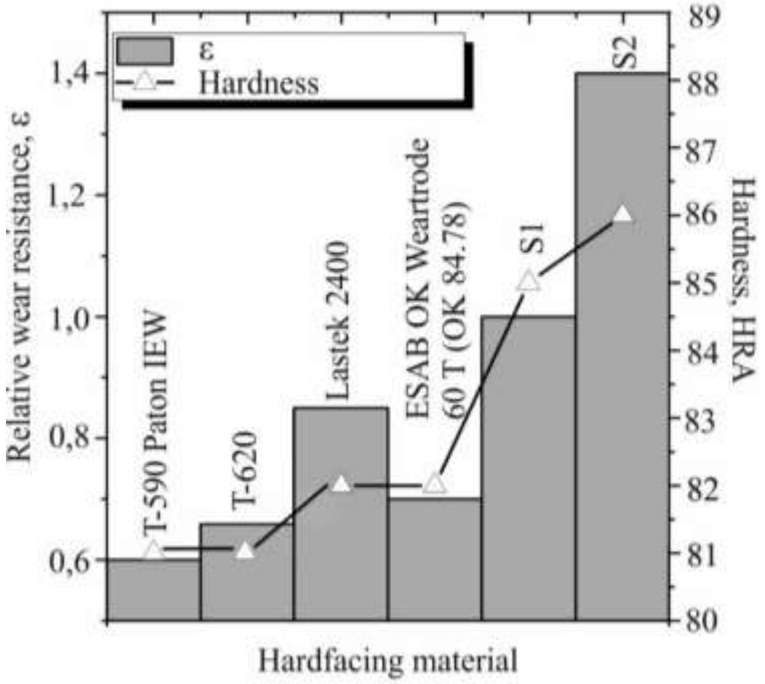

Fig. 6 Dependence of relative wear resistance ε (wear testing with fixed abrasive) and hardness on hardfacing material

It can be seen that investigated hardfacings (sample 1 and sample 2) are given in higher hardness and lower wear level, whereas serial production hardfacings are situated in higher wear level in conditions of abrasion wear.
Hardfacings systems of tested serial materials shown in Table 3.

Table 3 Serial hardfacing materials

Hardfacing material	Alloying system	Manufacturer
T-590	Fe-Cr-C-B-Mn	Paton IEW, Ukraine
T-620	Fe-Cr-Ti-C-B-Mn	Specelectrode, Russia
ESAB OK Weartrode 60	Fe-Cr-C-Mn-Si	ESAB, Sweden
Lastek 2400	Fe-Cr-V-Mn	Lastek Belgium NV, Belgium

Sample 1 shows hardness of 85 HRA with much higher wear resistance than serial hardfacing materials with more complex alloying systems. And sample 2, due to refinement of structure shows the highest abrasion wear resistance among tested materials and the highest hardness (~ 86 HRA).
To carried out the experiment in the real working conditions sample 2 was used for strengthening of the multi-section press extruder-screw for ceramic building materials (CBM) production (Fig. 7).
The multi-section extruder-screw is a working element of the widely-used press equipment for production of ceramic building materials (CBM). The working process includes: final processing of raw mass, its compression and passing to the formation zone of a raw bar. Extruder-screw consists of three separated sections of variable diameter (input section of Ø600 mm, transition section from

Ø600 to Ø500 mm, output section of Ø500 mm), which are mounted on the drive shaft of square cross-section, which serves for torque transmission.

Fig. 7 General view of multi-section extruder-screw for pressing ceramic building materials (CBM) after hardfacing

The production process of ceramic building materials (CBM) is mainly based on usage of raw components that are characterized with high hardness and works as abrasive materials in working zone (Mikul'skij and Saharov, 2007). Preparation of a mixture of those raw components, its transportation by a technological line and further formation of products is carried out with the process of intensive abrasive wear of the equipment.

Operating modes of multi-section press extruder-screw: – pressure diapason 3.0...3.7 MPa; – extruder-screw wrapping frequency 0.6 sec^{-1}; – compression percentage of raw mass 28...30%. Raw mass consists of homogeneous plastic mixture with abrasive inclusions. The raw materials for the preparation of the mixture are clays of different types, which differ in both chemical and particle size distribution (Komar, 1983). The chemical composition of clays varies in wide ranges (% wt.): 45...80 SiO_2; 8...28 (Al_2O_3 + TiO_2); 2...15 Fe_2O_3; 0.2...25 CaO; 0...4 MgO; 0.3...5 R_2O. The particle size distribution of the clay mass is characterized by great diversity. The clay component with a particle size < 5 μm in different clay rocks is 8...60%, the content of dusty component (5...50 μm) 6...55%, sand (> 50 μm) 3...32%.

Analysis of the surface appearance of the multi-section press extruder-screw during its operation showed that the screw wears on the front surface of the pen, which reduces the thickness of its sidewall, increases the gaps between it and the hull reduces the productivity of the press. Wear of the front surface of the pen is uneven: the intensity of the process increases with distance from the axis of the screw, which causes thinning of the sidewalls of the screw with the subsequent formation of sharpening of the walls to the periphery during exploitation.

Taking into account the above-described features of the shape changing of the screw during its operation, coating of multi-section press extruder-screw was carried out according to the following scheme (the diameter of the workpiece for surfacing should be 8… 10 mm smaller than the limited diameter of the finished screw):

- on the end surface of the screw in manual mode using the developed system (sample 2) Fe-Ti-Mo-B-C;
- on the front surface in the zone of more intensive wear, with the zone remote to the periphery, in a semi-automatic mode using the developed system (sample 2) Fe-Ti-Mo-B-C;
- on the intake part – zones on both sides of the sidewall, in a semi-automatic mode using the developed system (sample 2) Fe-Ti-Mo-B-C.

The optimal height of the deposited layer is 2…3 mm with a maximum allowable up to 5 mm. Exceeding the specified height leads to excessive fragility of the weld coating with the possible formation of chips on the surface. As a result of industrial testing in real conditions of ceramic brick production by working out a set of sections of multi-section press extruder-screws of press equipment the results of the conducted laboratory researches are completely confirmed.

The held probation showed results in increasing of the TBO period of extruder-screw for production of ceramic building materials by 2.2…2.4 times compared to the screws welded with serial electrodes brand Lastek 2400.

DISCUSSION

Analyzed equipment of industries, such as production engineering, construction, oil and gas, woodworking, tillage, etc., works in conditions of intense abrasion wear with high working speed and high cyclic and specific loads. Such conditions require materials not only with high hardness but with the structure that can works under such conditions. Restoring of wear parts of such equipment widely carried out by FCAW, and increasing the wear resistance can be provided by materials with fine grained and uniformly distributed hard particles in metal matrix structure. As shown in experiment, such structure was provided with using, as initial components, powders of pure metals and not the ferroalloys while FCAW. This led to “*in-situ*” synthesis reaction during FCAW and to formation fine structure that is different from structures obtained by other methods or by using ferroalloys.

Addition of Molybdenum to Fe-Ti-B-C led to refinement of the structure and, as a result, to increasing of hardness and wear resistance and its structure consist of refractory borides, carbides and their solid solutions. This electrode was chosen for restoring and increasing the wear resistance of extruder-screw, which is working part of equipment for production of building ceramic materials. Held test showed that Fe-Ti-Mo-B-C works 2.2…2.4 times better compared to serial electrodes brand Lastek 2400. According to the results of the bench and held tests, the developed material of the Fe-Ti-B-Mo-C system is recommended

for strengthening fast-wearing parts of technological equipment for the production of ceramic building materials (CBM). Also, using of Ti and Mo powders that is more economical than using of expensive Nb, Co, W powders.
Further tests of the developed materials as hardfacing coating on working elements is desire. Investigations of proposed Fe-Ti-Mo-B-C system with not equimolar ratio of Mo/Ti can be done. Comparative analysis of developed materials with systems based on W can be done.

CONCLUSION

Working conditions of equipment for processing of abrasion masses, logs peeling, production of ceramic building materials, fuel briquettes, dry compounds were analyzed.
Using of pure metal powders while FCAW led to "*in-situ*" synthesis which provided formation of fine-grained structure with uniformly distributed hard particles. Such structure shows higher wear resistance under abrasion than the modern serial production electrodes. As well as, combination of Ti and Mo in equimolar ratio with B_4C system affects on structure formation due to appearance of new phases and significantly grain refinement of boride phase, which affects with increasing of hardness and wear resistance while bench test. Hardfacing coating based on Fe-Ti-Mo-B-C system shows the highest wear resistance with hardness (~ 86 HRA) among other tested materials. As a result, investigated hardfacing (sample 2) based on Fe-Ti-Mo-B-C was used for increasing a wear resistance of extruder-screw for manufacturing of building ceramic materials. Using of proposed system leads to improvement of TBO period of extruder-screw equipment by 2.2…2.4 times compared to the screws welded with serial electrodes brand Lastek 2400.
Using of proposed systems based on Fe-Ti-B-C and Fe-Ti-Mo-B-C leads to improvement of quality of production industries equipment that works in conditions of intense abrasion wear by increasing the abrasion resistance and, as a result, duration of TBO period.

REFERENCES

Badisch, E. and Miller, C. (2003). Abrasive wear of high speed steels: influence of abrasive particles and primary carbides on wear resistance. Tribology International, 36, pp. 765-770.

Ivanov, O.O. et al. (2018). Restoration of equipment for woodworking. Problems of Tribology, 1, pp. 99-105.

Ivanov, O.O. et al. (2019). Increasing the durability of working elements of equipment for abrasive containing masses processing. Problems of Tribology, 24 (3/93), pp. 14-21.

Jilleh, A. et al. (2013). Microstructural and mechanical properties investigation of TiC reinforced hardface alloy deposited on mild steel substrate. Transactions of the Indian Institute of Metals, 66(4), pp. 433-436.

Komar, A.G. (1983). Stroitel'nye materialy i izdeliya. Moscow: Vysshaya shkola.

Liu, D. et al., (2012). Effects of titanium additive on microstructure and wear performance of iron-based slag-free self-shielded flux-cored wire. Surface and Coatings Technology, 207, pp. 579-586.

Lutsak, D.L. et al., (2016). Formation of Structure and Properties of Composite Coatings TiB2- TiC-Steel Obtained by Overlapping of Electric-Arc Surfacing and Self-Propagating High-Temperature Synthesis. Metallofiz. Noveishie Tekhnol., 38(9), pp. 1265-1278.

Mikul'skij, V.G. and Saharov, G.P. (2007). Stroitel'nye materialy. Moscow: ASV.

Pokhmurska, G.V. and Voitovych, A.A. (2015). Impact-abrasive Wear of Surface Layers Weld with Cored Wire of C-Cr-B-Fe System. Naukovyi visnyk NLTU Ukr, 25(3), pp. 129-135.

Qi, X. et al. (2011). Effects of vanadium additive on structure property and tribological performance of high chromium cast iron hardfacing metal. Surface and Coatings Technology, 205, pp. 5510-5514.

Sadeghi, F. et al. (2017)/ The effect of Ta substitution for Nb on the microstructure and wear resistance of an Fe-Cr-C hardfacing alloy. Surface and Coatings Technology, 324, pp. 85-91.

Wang, Yu Xi and Zhang, S. (2014). Toward hard yet tough ceramic coatings. Surface & Coatings Technology, 258, pp. 1-16.

Wang, X. et al. (2008). Microstructure of the Fe-based hardfacing layers reinforced by TiC-VC-Mo2C particles. Surface and Coatings Technology, 202, 8, pp. 1502-1509.

Wang, X. et al., (2008). Microstructure and wear properties of the Fe-Ti-V-Mo-C hardfacing alloy. Wear, 265(5-6), pp. 583-589.

Zhang, M. et al. (2018). Effect of Molybdenum on the Wear Properties of (Ti, Mo)C-TiB2-Mo2B Particles Reinforced Fe-Based Laser Cladding Composite Coatings. Journal of Tribology, 140(5).

Abstract: In this work were analyzed factors that leads to wearing of equipment of production engineering, construction, oil and gas, woodworking, tillage industries. Was established that traditional hardfacing materials based on the Fe-Cr-C system are not effective for improvement of abrasion resistance of elements of equipment for production of ceramic building materials due to working conditions. The aim of this work was to increase a durability of that equipment by using of flux cored electrodes with reaction components that provide “in-situ” synthesis, which leads to fine-grained structure of refractory borides and carbides and their solid solutions with increased hardness. Powders of Ti, Mo, B4C and their combinations were used. Structure of the hardfacing coatings were investigated by method of metallography, scanning electron microscopy (SEM). Using of pure metal powders led to forming a fine-grained structure with refractory borides and carbides and their solid solutions. It was investigated that the offered material based on Fe-Ti-Mo-C-B system used for increasing the wear resistance of extruder-screw for production of ceramic building material can increase the TBO period in 2.2-2.4 times in comparison with serial hardfacing materials based on Fe-Cr-C system.

Keywords: flux cored electrodes, abrasion resistance, hardfacing, microstructure, extruder-screw