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# Research of abrasive erosion wear for Fe-C-Cr-B hard layers

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## 1. Introduction

Due to wear the industrial equipment losses reach 4-5% of the net national product, due to friction – 30-40% of generated power is lost, due to wear of machine parts surfaces 80-90% damages occur [1]. Though in many cases damages occur due to minor wear (up to 0.2 mm [2]), the parts of agricultural and mining machines wear down by tens of millimeters, sometimes reaching 42% of their mass [3].

Wear intensity may be caused by the abrasive particle characteristics such as type of abrasive material, hardness, particles shape, or by the properties of machine parts material such as composition, structure, hardness, quantity of reinforcement and its size [4-8].

Some machine parts may be affected by an abrasive under large contact pressure (in plough chisels and ploughshares, mining and construction machine buckets and teeth) at low rate or at high rates (sand-blower blades, pump rotors, working wheels).

Fast wear of these parts (up to 12.7 mm/h [9]) put these machines to frequent repair. Downtime of machines increases their exploitation cost and expenses for spares. For this reason resistance to wear is of paramount importance.

The study [10] has proved that abrasive wear of hard layers Fe-C-Cr-B, Fe-C-Cr-Mo (by silica sand) is mostly caused by the quantity of elements forming carbides and borides. An increase in carbon content and accompanied increase in hardness reduces wear. When carbon of a hard layer reaches 2.8-3.5% C, wear becomes minimal. With an increase in carbon amount wear remains constant (Fig. 1). Wear of hard layers is directly influenced by the ratio of the sums of hard layer elements (Fe+Cr) and (C+B). Materials with lower ratio (in the interval 23…68) are more resistant to wear [10] (Fig. 1, b).

The study [11] has proved that during welding process the resistance of layers to abrasive wear could be increased by alloying them with graphite, boron, boron carbide and steel P6M5 chips.

Thorough investigation of abrasive erosion wear of structural materials is described in the studies [12-15]. Wear intensity is strongly affected by: abrasive material (harder abrasive causes usually more intensive wear), abrasive particles size (maximal wear intensity at particles of 0.2-0.3 mm), particles impact velocity rate (the higher the rate the more intensive wear), abrasive particles impact angle (maximal wear at 25$^o$-45$^o$ angle), temperature and other factors [13].

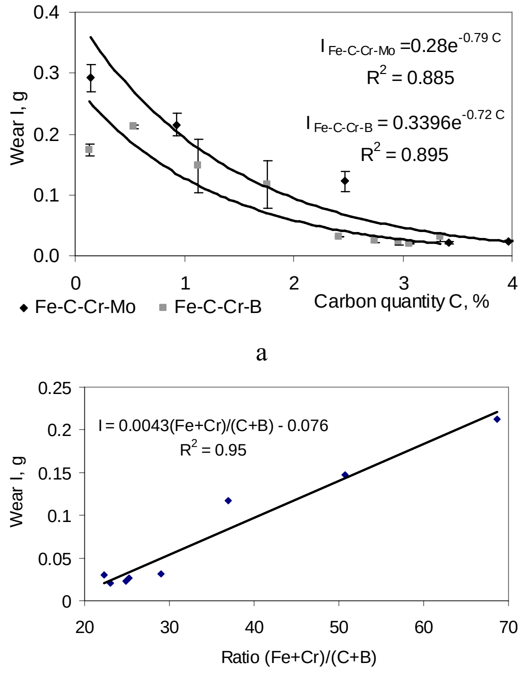



Fig. 1 Influence of hard layers composition on abrasive wear [10]: a – carbon content; b – ratio of the elements (Fe+Cr)/(C+B) forming carbides and borides

The particles impact angle has a different effect on wear intensity of soft and hard material. The highest rate of soft and ductile materials wear is when the particles are striking at an angle of 20$^o$–30$^o$ (micro-cutting proceeds), the highest wear of hard and brittle materials is at the particles impact angle close to normal [13-15].

Wear of an alloy of two different hardness phases (soft matrix with carbides) is not the sum of soft and hard phases wear. In this case wear occurs at the wear surface of the quantities of these phases, and it is the whole complex of abrasive characteristics and working conditions [15].

The rate of wear at different impact angles is affected by hard phase content in the alloy. With 90% of a hard phase in an alloy, when the angle varies from 30$^o$ to 90$^o$, wear increases twice, and with 70% of a hard phase the wear increases 2.25 times due to the angle variation [15].

A quite different effect on the wear mechanisms is provided by the particles impact angle on the surface. At an oblique particles impact angle on the surface the micro-cutting processes prevail, at an angle close to the perpendicular the surface-multiple plastic deformation and fatigue processes are prevalent. The growing and combining of microcrack caused by the material fatigue leads to the loss of material fragments [12].

## 2. Testing procedures

Abrasive erosion wear has been tested according to GOST 23.201-78 [16] using the Centrifugal Accelerator of Kleis (CAK) shown in Fig. 2. Test parameters are: room temperature, silica sand with particles size - 0.25-0.5 mm, particle impact velocity – 50 m/s, impact angles – $30^o$ and $90^o$, abrasive consumption – 6 kg, 15 samples simultaneously.

The wear resistant boron micro-alloyed Hardox 400 steel (69 HRA) was used as reference material. Its composition is given in Table 1. Dimensions of the samples are 20×15×6 mm. Before and after tests the samples have been cleaned in an ultrasound bath, washed with alcohol and then dried. The wear has been evaluated by weighing the samples on scales Sartorius AC210S (accuracy 0.1 mg) also before and after testing.

Table 1

Composition of reference steel Hardox 400

| Chemical composition, wt. % | | | | | | | |
|---|---|---|---|---|---|---|---|
| C | Mn | Cr | Si | Mo | Ni | B | Other elements |
| 0.27 | 1.6 | 0.3 | 0.7 | 0.25 | 0.25 | 0.004 | S-0.01; P-0.025 |

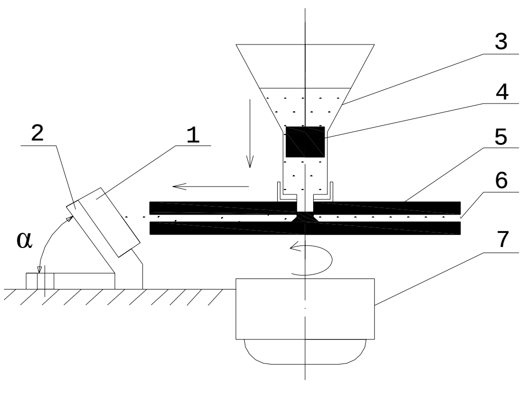



Fig. 2 Abrasive erosion tester for testing materials in abrasive particle jet [12]: *1* – specimen, *2* – abrasive particles vessel, *3* – shield, *4* – rotor, *5* – drive motor, *6* – rotation frequency gauge

The study [17] has confirmed that in the two layers welded surfaces the chemical composition of the second layer is practically the same as that of the pure welding metal. In order to have the sufficient thickness of the layer and taking into account the results shown previously, the samples were welded into two layers and have been used for testing.

Chemical composition of the welded samples has been estimated with the BELEC-compact-lab-N spectrometer. The results are presented in Table 2.

Hardness of the welded samples has been measured with the hardness tester TK-2M, 600 N load (HRA scale).

The aim of this study is to investigate influence of carbon and chromium content on abrasive erosive wear of arc welded layers.

## 3. Results

3.1 Composition of layers

The Fe-C-Cr-B coating were applied by arc-welding technique electrodes (671-677) [10], providing constant content of carbon and other elements and varying the content of chromium and iron. However, during the welding process the carbon amount is varying due to a chromium effect on the elements assimilation (Table 2). The higher chromium amount (from 1.1 to 27.6%) the higher amount of carbon (from 1.55 to 2.49%) is in the welded layer. The amounts of boron, the element enhancing resistance to wear, have been varied from 0.48 to 0.75%. The thickness of the layers – 3-4 mm.

The constant amount of chromium from 14.1 to 15.7% and the varying amount of carbon in layers 682-688 have been obtained with 0.15-2.92% of carbon content. The amount of boron has been varying from 0.508 to 0.688% (Table 2).

Table 2

Composition of a set of welded hard layers Fe-C-Cr-B

| Sample | Chemical compositions of deposited layers, wt. % | | | | | | | | | | Hardness, HRA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Mo | Ni | Ti | B | Other | Fe | |
| Hard layers with C fixed, Fe and Cr - quantity variables | | | | | | | | | | | |
| 671 | 2.49 | 1.94 | 0.97 | 27.6 | 0.05 | 0.05 | 0.31 | 0.673 | 0.55 | 65.3 | 79 |
| 672 | 2.37 | 2.26 | 1.08 | 18.7 | 0.04 | 0.11 | 0.75 | 0.748 | 0.66 | 73.3 | 78 |
| 674 | 2.62 | 1.58 | 0.94 | 15.0 | 0.04 | 0.09 | 0.78 | 0.791 | 0.51 | 77.7 | 82 |
| 675 | 1.88 | 1.55 | 1.04 | 8.1 | 0.02 | 0.07 | 0.57 | 0.546 | 0.37 | 85.8 | 77 |
| 676 | 1.60 | 1.44 | 0.90 | 4.4 | 0.01 | 0.05 | 0.59 | 0.555 | 0.24 | 90.2 | 80 |
| 677 | 1.55 | 1.12 | 0.90 | 1.1 | 0 | 0.04 | 0.43 | 0.480 | 0.17 | 94.2 | 76 |
| Hard layers with C – quantity variable, Cr – quantity fixed | | | | | | | | | | | |
| 682 | 2.92 | 2.03 | 0.96 | 14.1 | 0.03 | 0.08 | 0.92 | 0.688 | 0.49 | 77.8 | 82 |
| 685 | 2.05 | 1.48 | 0.99 | 15.7 | 0.03 | 0.09 | 0.18 | 0.592 | 0.39 | 78.5 | 78 |
| 686 | 1.12 | 1.50 | 0.88 | 14.5 | 0.03 | 0.07 | 0.11 | 0.531 | 0.40 | 80.8 | 75 |
| 687 | 0.45 | 0.69 | 0.61 | 15.0 | 0.03 | 0.05 | 0.12 | 0.508 | 0.22 | 82.3 | 73 |
| 688 | 0.15 | 1.38 | 0.69 | 15.5 | 0.03 | 0.03 | 0.06 | 0.577 | 0.39 | 81.2 | 68 |
| Other hard layers | | | | | | | | | | | |
| 590 | 2.05 | 2.22 | 1.94 | 15.4 | 0.35 | 1.02 | 0.34 | 0.223 | 0.48 | 76.0 | 73 |
| 0686 | 1.17 | 1.57 | 1.01 | 18.1 | 4.37 | 0.11 | 0.12 | 0.003 | 0.73 | 72.8 | 64 |
| 60 | 0.62 | 0.35 | 1.03 | 3.6 | 0 | 0.04 | 0.03 | 0 | 0.24 | 94.1 | 73 |
| 9313 | 0.44 | 2.28 | 0.67 | 7.4 | 0.96 | 0.07 | 0.09 | 0.001 | 0.44 | 87.6 | 76 |
| Other elements - P+S+Cu+Al+Ni+V+Nb+Co+W+As | | | | | | | | | | | |

The microstructure was analyzed with an optical metallographic microscope, SEM (JEOL JSM-5600) and the samples were prepared according to the standard methods.

In the SEM micrograph of welded 674 layer, small carbides of needle shape (about 20 μm width) were obtained. Carbide Volume Fraction in all welded layers calculated by the Eq. [18] is in agreement with obtained

SEM micrographs.

$$CVF = 12.3(\%C) + 0.55(\%Cr) - 15.2$$

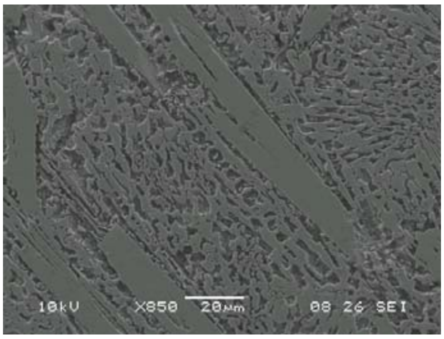



Fig. 3 Microstructure of welded layer (sample 674, SEM, ×850)

Carbides size evaluated allows to conclude that they are about 10 to 20 times smaller then abrasive particles. The hardness is 800-1100 HV and 910-1470 HV for $SiO_2$ and $(Cr, Fe)_7C_3$ respectively. Taking into account above mentioned facts carbides can not be easily removed by abrasive particles and in the case of wear by single impacts of abrasive particles the matrix play an important role providing the support of carbides [12].

3.2 Abrasive erosion wear

The results of erosive testing of 671 to 677 materials (Fig. 4) show that there is no direct effect of elements content on wear as it has been estimated in the case of abrasive wear [10]. In the layers of 674-677 with an increase in carbon content from 1.55 to 2.62%, chromium content - from 1.1 to 15.0%, an adequate reduction in wear has not been noticed. In separate cases, i.e. in 675 and 676 a significant difference indicates the wear values obtained at different angles of the abrasive stream striking the surface.

The 677 hard layer having a minimal amount of carbon and chromium (1.55 and 1.1%, respectively) among the tested 671-677 materials has shown the lowest wear resistance at both angles tested. This minimal resistance to cutting is considered to be due to very low hardness of the layer (76 HRA). When the particles are striking at $30^o$ angle, layers 671, 675 and 676 wear minimally. Layer 671 possesses maximal amounts of carbon and chromium 2.5 and 27.5%, respectively, while layers 675 and 676 have 1.6 -1.88% C and 4.4-8.1% Cr, respectively. The difference in hardness of these layers is insignificant (77-80 HRA). Layer 671 is likely to be ductile because of a surplus of chromium in it. Whereas neither of the welded hard layers – 671-677 at particles impact angle of $90^o$ can equal the resistance to abrasive erosion wear of steel Hardox 400 (hard layers possessing carbide phase are more brittle). It is likely to result from the lower hardness of steel Hardox 400. This steel undergoes longer plastic deformation rather than the formation of cracks and crumbling of material.

Average wear of samples group 671-677 at the perpendicular particles impact on the surface was 6% greater than the wear at the sloping particles impact.

Evaluating the wear of hard layers containing the varying carbon and constant chromium amounts (682-688, Fig. 5) it is evident that only the wear of layer 688 (0.15% C, 15.5% Cr) when abrasive is striking at the angle of $90^o$ is comparable to the wear of steel Hardox 400. It is likely due to the composition of the layer identical to that of stainless steel. The wear rate of other layers is much higher. Harder layers such as 682-687 with 75-82 HRA are less resistant to intensive plastic deformation because they are more brittle. However, with the particles impact angle of $30^o$ the result is opposite. In this case layer 688 wears 13% more, while the others (0.45-2.92% C) wear less to about 9%.

Average wear of 682-688 samples group at perpendicular particles impact on the surface is 15% lower than the wear under the sloping particles stream.

When estimating the other hard layers (Fig. 6), the reference steel Hardox 400 under the abrasive particles striking the surface at $90^o$ is more resistant to wear than all hard layers given for comparison. Out of all layers presented in Fig. 6, layer 60 has worn the least and uniformly (at angles $30^o$ and $90^o$) containing the following amounts of elements: C – 0.62%, Cr – 3.6%, Mn – 1%, Si – 0.35%.

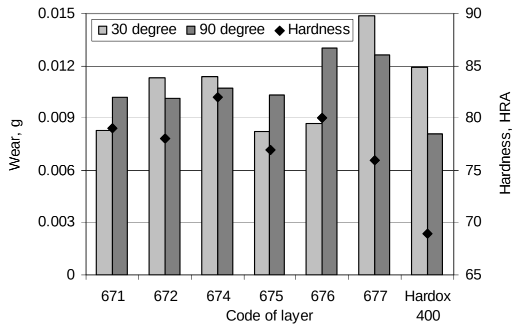



Fig. 4 Hardness and wear of constant C, varying Fe and Cr amounts in the hard layers (671-677) in abrasive erosion wear investigation

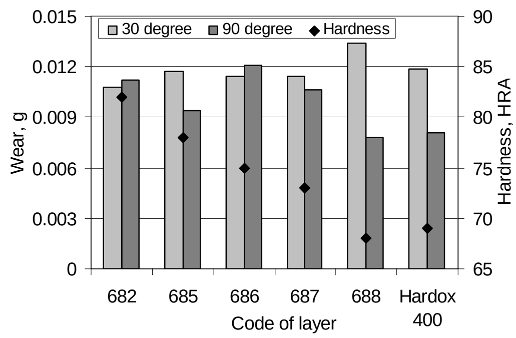



Fig. 5 Hardness and wear of hard layers (682-688) with varying carbon and constant chromium amounts in the abrasive erosion wear test

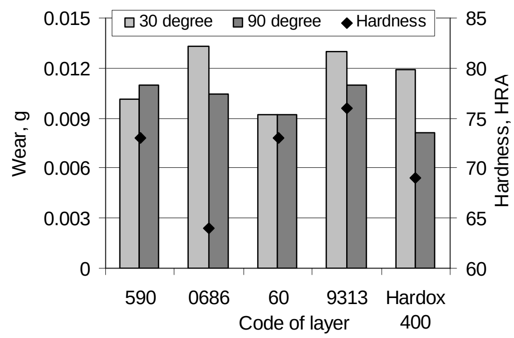



Fig. 6 Hardness and wear of other hard layers (Table 2) in the abrasive erosion wear test

The wear of this layer is lower than the wear of most layers 671-677 and 682-688.

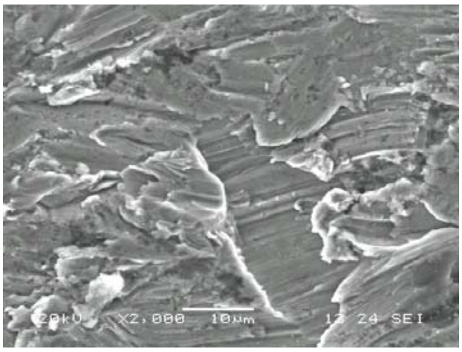
At the abrasive particles impact angle of 90° only layer 688 (Figs. 4-6) will diminish wear by 4 % compared to steel Hardox 400. At the abrasive particles impact to surface angle of 30°, layers 675, 671, 676 will diminish wear by 27-31%, layer 60 – by 23%.

Estimating the obtained result and being aware that under abrasive wear layers Fe-C-Cr-B wear 6-8 times slower than boron micro-alloyed steel [10], it is expedient to recommend these layers for the use under the complex abrasive/abrasive erosion wear conditions.

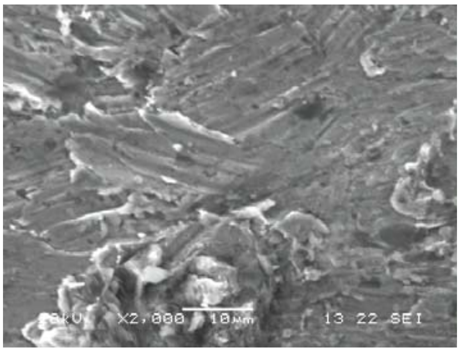
### 3.3. Estimation of results, mechanisms of wear

At different angle of the particles impact on the wearing surface (Figs. 7-8) SEM images of wear surfaces indicate a different abrasive erosion wear mechanism. As a rule [12], at an angle of 30° the wear of steels is greater than in case of the particles striking at 90° angle, however in welded hard layers it has not always proved correct. When the surfaces of different hardness are subjected to the sloping sand particles stream, wear prevails due to the microcutting effect of the particles. In soft layers (with low carbon content, Fig. 7, a) the traces of intensive plastic deformation are evident – microcuts of 20-25 μm width and shifted surface segments, in the reference steel - cuts to 50 μm length, while on the surfaces of very hard layers there is no signs of long distance sliding (Fig. 7, b), the traces of both cutting and brittle destruction are being formed.

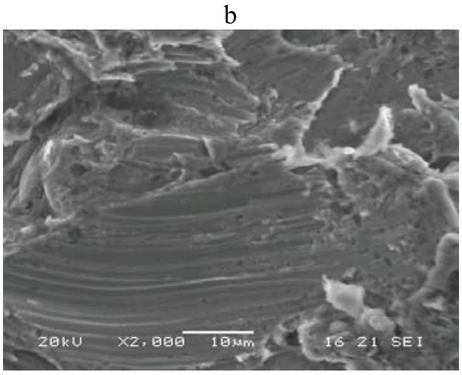
When abrasive particles are striking the surfaces of different hardness at normal impact angle, the images of the material damage are rather similar with pronounced cracking taking place (Fig. 8). There, the wear is the result of fatigue multiple plastic deformations irrespective of material hardness. On the surfaces, especially of higher hardness, microcracks are seen. The samples, cleaned by an ultrasound method after testing, still contain some abrasive particles (Figs. 7, b and 8, b). Harder surfaces are seen to be covered with fine particles of the cracked surface from 5×5 to 10×20 μm (partly separated from surface, Fig. 8, b). Even finer wear particles from 5×5 to 7×7 μm cover the reference steel Hardox 400, (Fig. 8, c). This steel without a brittle phase (carbide structures) when subjected to plastic deformations of abrasive particles undergoes




a

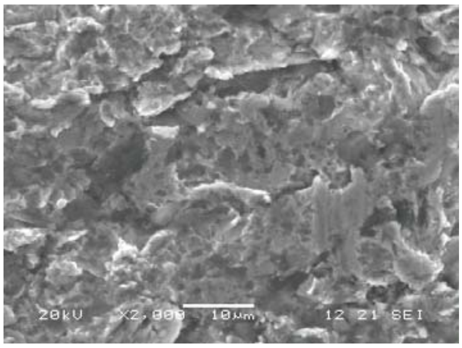



b

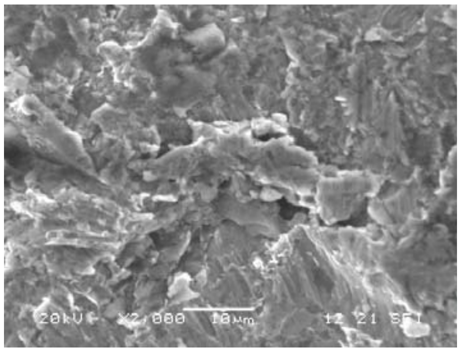



c

Fig. 7 SEM images of the layers affected by abrasive erosion wear at 30° angle: a – sample 688, b – sample 682, c – reference Hardox 400




a

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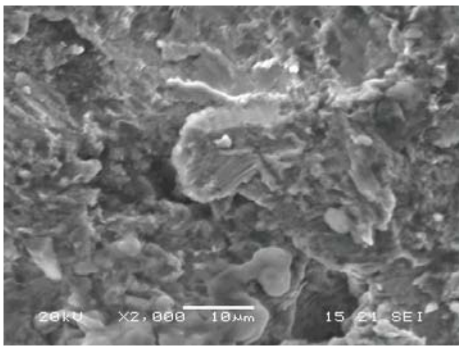


c

Fig. 8 SEM images of the layers affected by abrasive erosion wear at 90° angle: a – sample 688, b – sample 682, c – reference Hardox400 plastic deformation changes. Plastic deformation consumes energy but do not lead to the direct material fracture, that leads to the decrease of the wear rate.

This phenomenon explains the lower wear of this steel than the wear of hard layers in many cases.

The wear mechanism (due to plastic deformations, cracks) at the angle of 90° is defined by the image of the surface of sample 677 presented in Fig. 9. There a cracked particle separated from the surface is evident.

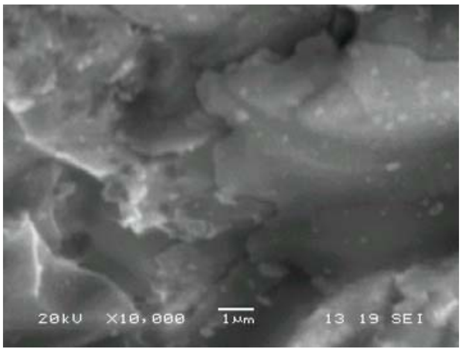


Fig. 9 Surface of the sample affected by plastic deformations of the abrasive erosion wear, sample 677, 90° (micro-cracks, micrometric size particles separation from the surface are evident)

**4. Conclusions**

1. When abrasive particles impact the surface at an angle of 30°, micro-cutting wear prevails; when the particles impact the surface perpendicularly, the wear due to fatigue processes caused by multiple plastic deformation/re-deformation dominates;

2. Under abrasive erosion wear conditions the wear of hard layers is lower if compared to Hardox 400 up to 31% at the abrasive particles impact angle of 30°, and up to 4% at the perpendicular particles impact on the surface;

3. Abrasive erosion wear intensity of hard layers is not directly proportional to the material hardness and its chemical composition. Hard layers affected by the abrasive stream at 30° impact angle has the minimal wear if they contain the maximal amounts of carbon and chromium studied (2.49 and 27.6%, respectively) comparing to the ones containing (1.6-1.88% C and 4.4-8.1% Cr, respectively). At the abrasive particles impact angle of 90°, the layers with low carbon (0.15%) and high chromium (15.5%) amounts have the highest resistant to wear (stainless steel type).

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APVIRINTŲ KIETŲJŲ Fe-C-Cr-B SLUOKSNIŲ ABRAZYVINIO EROZINIO DILIMO TYRIMAS

R e z i u m ė

Atliktas elektrolankiniu metodu apvirintų kietųjų sluoksnių abrazyvinio erozinio dilimo tyrimas. Nustatyta, kad kietųjų sluoksnių paviršių veikiant nuožulniam abrazyvo dalelių srautui vyrauja dilimas mikropjovimu, o veikiant statmenam srautui, – dilimas dėl mikronuovargio procesų. Abrazyvinio erozinio dilimo sąlygomis apvirinimas kietaisiais sluoksniais nudilimą gali sumažinti iki 31%, kai abrazyvas krinta į paviršių 30° kampu, ir tik 4%, kai abrazyvas krinta statmenai į paviršių. Esant nuožulniam abrazyvo dalelių srautui, atspariausi abrazyviniam eroziniam dilimui yra anglingi (1.6 - 1.9%), 4 - 8% chromu legiruoti sluoksniai, kai srautas statmenas paviršiui, atsparesni yra mažaangliai (0.15%), gausiai chromu (15%) legiruoti sluoksniai.

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RESEARCH OF ABRASIVE EROSION WEAR FOR WELDED HARD Fe-C-Cr-B LAYERS

S u m m a r y

This study presents the research related with abrasive erosion wear of electric-arc welded hard layers. It is estimated, that when the abrasive particles affect the hard layers surface at oblique angle the wear by microcutting prevails, when they strike perpendicularly – the wear is caused by microfatigue processes. Under abrasive erosion conditions the wear of electric arc welded hard layers is lower if compared to Hardox 400 up to 31% at the abrasive particles impact angle of 30°, and only up to 4% at the perpendicular particles impact. Under the abrasive particles stream impacting the surface at oblique impact angle the most resistant to wear are the layers alloyed with 1.6-1.9% carbon and 4-8% chromium while under the normal impact the most resistant to wear are the low carbon layers alloyed with 0.15% C and high chromium layers alloyed with 15% Cr.

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ИССЛЕДОВАНИЕ АБРАЗИВНО-ЭРОЗИОННОГО ИЗНАШИВАНИЯ НАПЛАВЛЕННЫХ Fe-C-Cr-B ТВЕРДЫХ СЛОЕВ

Р е з ю м е

В настоящей работе проведены исследования абразивно эрозионного изнашивания твердых слоев, полученных электродуговой наплавкой.

Определено, что при воздействии пологого потока абразивных частиц, изнашивание поверхности происходит из-за микрорезания, а в случае перпендикулярного падения частиц на поверхность – изнашивание происходит из-за микроусталостных процессов. Износ (по сравнению с бором микролегированной сталью Hardox 400) наплавленных поверхностей меньше до 31% при пологом потоке абразивных частиц, и до 4% меньше при перпендикулярном потоке.

Наиболее стойкими абразивно эрозионному изнашиванию при пологом потоке абразивных частиц являются слои, содержащие 1.6 - 1.9% углерода, 4 - 8% хрома, в то время, как при перпендикулярном потоке наибольшей износостойкостью обладают малоуглеродистые (0.15%), содержащие большое количество хрома (15%) слои.

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