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INFLUENCE OF HIGH-FREQUENCY MECHANICAL VIBRATIONS OF THE ITEM ON STRUCTURE AND WEAR RESISTANCE OF KH10R4G2S DEPOSITED METAL

G.V. POKHMURSKAYA[1], **M.M. STUDENT**[2], **A.A. VOJTOVICH**[3], **A.Z. STUDENT**[2] and **A.R. DZYUBIK**[3]

[1]Technical University of Chemnitz
09107, Chemniz. E-mail: pokhmurska@mb.tu-chemnitz.de
[2]G.V. Karpenko Physico-Mechanical Institute, NASU
5 Nauchnaya Str., 79601, Lviv, Ukraine. E-mail: student-m-m@ipm.lviv.ua
[3]«Lviv Polytechnic» National University
12 Stepan Bandera Str., 79013, Lviv, Ukraine. E-mail: andrsibox@gmail.com

The paper presents the results of studies of the effect of high-frequency (100 Hz) mechanical vibrations on microstructure and wear resistance of metal, deposited with PP Kh10R4G2S wire and OSTs45M flux. It established that when horizontal vibration is used, deposited metal solid solution, uniformly saturated with fine iron-chromium borides (FeCr)B, prevails in the structure. Homogeneous structure improves wear resistance by 2.0–2.5 times. 9 Ref., 1 Table, 5 Figures.

Keywords: *surfacing, flux-cored wire, vibration, microstructure, fatigue life, wear pattern*

Earlier conducted studies revealed that the form and size of carbide inclusions influence deposited metal performance [1]. Deposits produced with flux-cored wires (FW) of Fe–Cr–B–C system of hypereutectic composition are characterized by precipitation of carboboride dendritic axes of the first and second orders in the microstructure [2–4]. Pointed shape of hard inclusions, however, is a source of stress concentration, from which microcracks initiate, which, in its turn, leads to lowering of weld metal load-carrying capacity. It was also found previously [5, 6] that both mechanical characteristics of weld metal and its wear resistance are significantly increased at application of vibration during the surfacing process [7, 8]. The aim of this study was to optimize the amplitude of mechanical vibrations in the substrate during deposition to ensure high values of hardness and wear resistance of the deposited metal.

Deposited layers were produced on a substrate of mild steel St3sp under a layer of OSTs45M flux (composition in wt.%: 44 SiO_2, 44 MnO, <2.5 MgO, 6–9 CaF_2, <6.5 CaO, <2 Fe_2O_3, <0.15 S, <0.15 P) using flux-cored wire PP Kh10R4G2S. FW diameter was 2.6 mm with 25 % fill factor.

Samples of 300×150×10 mm size were surfaced. Their horizontal or vertical vibration was carried out with a frequency of 100 Hz at the amplitude of 70 and 300 μm. Horizontal vibration was applied across the deposited bead. Before surfacing, welding consumables were dried at 250 ° temperature for 2.5 hours. Beads were deposited with ABS suspended head with DC power supply (PSO 500 generator). Surfacing parameters were as follows: current of 420 A, arc voltage of 30–32 V, FW feed rate of 73 m/h, arc travel speed of 21 m/h, bead overlapping of 30 %.

Phase analysis was performed in X-ray diffractometer D8 Discover using Co-radiation. Microstructure was examined in electron microscope EVO 40 XVP. Axio Visio software was used for quantitative estimate of the dimensions of structural components in the deposited layers; inclusion area was compared with unit area of the microsection in the longitudinal plane.

Modulus of elasticity was measured by dynamic indentation with 50 g load. Scratch test (penetration depth, tangential force) was also carried out at 40 g load with dwell time under load of 40 s, and scratch length of 956 μm. Direction of scanning was across the bead.

Wear resistance of deposited layers at abrasive wear with loose abrasive was evaluated according to GOST 23.208–79. In particular, dried quartz sand with particle size of 200–1000 μm was continuously fed into the zone of rubber disc contact with the sample. Friction velocity was 0.3 m/s, and the force of its pressing to the sample was 2.4 kN. Abrasive wheel with CM 2 ceramic binder was used to determine the deposited layer wear by fixed abrasive. Linear velocity of friction was 0.8 m/s, load in linear contact zone was 1.5 kN. Length of the test path was 720 m. Impact wear was assessed at impact force of 12 kJ, using a sphere of 25 mm diameter from ShKh15 steel,

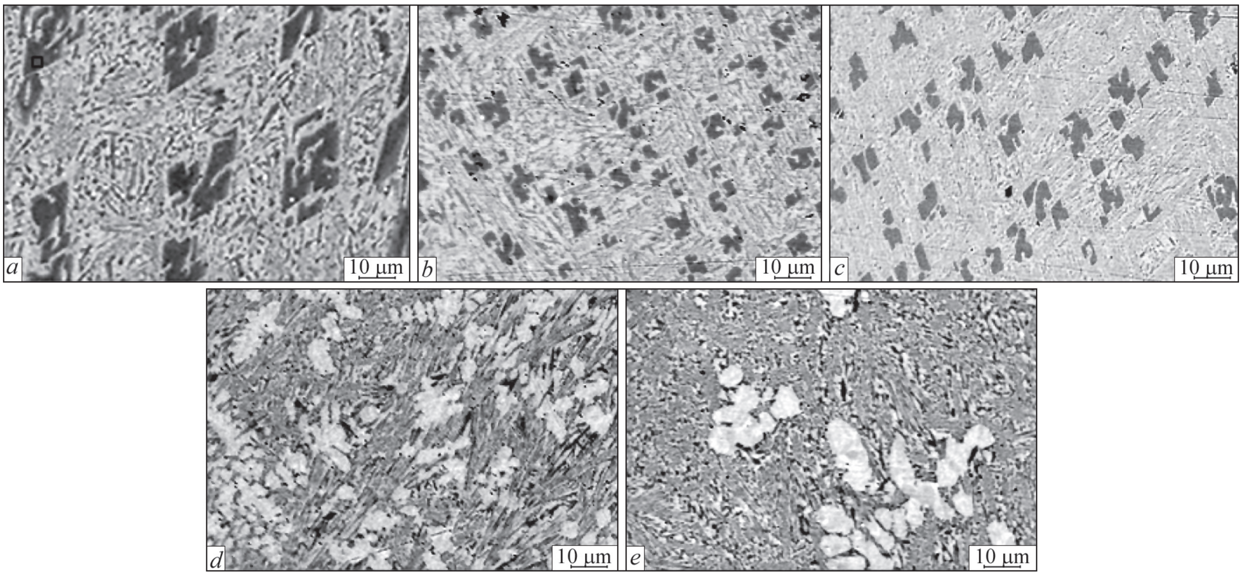

Figure 1. Microstructure in bead crest of metal deposited with PP Kh10R4G2S wire: *a* — without vibration; *b*, *c* — at vertical vibration; *d*, *e* — at horizontal vibration; at amplitude of 70 µm (*b*, *d*), 300 µm (*c*, *e*)

which hit the tested surface with a frequency of 40 s^{-1}. Experiment duration was 3600 s. Sample weight loss was determined with an accuracy of up to $2\cdot10^{-4}$ g in electronic scales.

Results and their discussion. Composition of the layers deposited without vibration included such phases as ferrochrome (FeCr), ferroboron (Fe_2B) and iron-chrome boride (FeCr)B [9] (Figure 1).

Metallographic examinations showed that vibration influences the size and shape of hard inclusions. On the crests of beads formed without vibration, the size of the area of isolated inclusions of (FeCr)B phase is 10–150 µm^2 (Figure 2, *a*). Surfacing samples using vertical vibration with the amplitude of 300 µm reduced the size (Figure 2, *b*) of borides (FeCr)B, the spread of their area was 10–30 µm^2. Application of horizontal vibration during surfacing revealed that hypereutectic structural components are refined even more. In particular, at maximum amplitude of 300 µm a significant refinement of iron-chromium borides (FeCr)B was clearly recorded, the size of the area of their isolated inclusions being 2–5 µm^2 (Figure 2, *c*). Furthermore, at horizontal vibration of a sample, formation of FeCr matrix phase in the form of unequiaxed grains was found in the deposited layer microstructure (Figure 1, *d, e*). At oscillation amplitude of 70 µm, their width and length ratio on the crests of the beads was 10–40 µm (Figure 1, *d*), and at the amplitude of 300 µm, these dimensions decreased to 5–30 µm (Figure 1, *d*). Presence of a small amount of FeCr matrix grains without inclusions enables relaxation of stresses, induced in subsequent operation of the deposited metal (Figure 2).

Dynamic indentation of the metal deposited with additional vibration, was performed to assess its mechanical properties. It was found that the greatest resistance to indenter penetration is in good agreement with the fine-grained microstructure on the bead crest and high density of hard (FeCr)B particles. Moreover, at horizontal vibration with the amplitude of 300 µm, the modulus of elasticity was equal to 331 GPa, which is significantly higher than the value obtained on samples deposited with application of vertical vibration (297 GPa), and without its application (295 GPa). This result may be an indication of the influence of mechanical vibrations on the level of weld metal po-

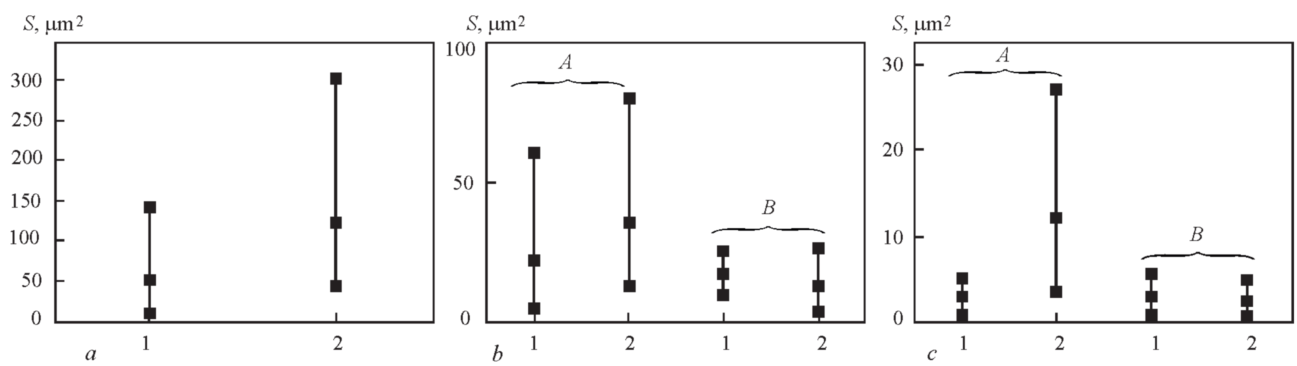

Figure 2. Change of area *S* of inclusions (1.6Fe + 0.4Cr)B; *a* — without vibrations; *b*, *c* — at vertical and horizontal vibration: *1* — on bead crest; *2* — in their overlapping zone; *A*, *B* — at the amplitude of 70 and 300 µm, respectively

Wear of samples with deposited layers, g

Parameter	Without vibration	Horizontal vibration		Vertical vibration	
Amplitude, μm	0	70	300	70	300
Wear with fixed abrasive	0.035	0.030	0.015	0.10	0.150
Wear with loose abrasive	0.020	0.015	0.01	0.045	0.035
Impact wear	0.009	0.0005	0.0007	0.005	0.004

rosity. After all, if we take into account the values of the modulus of elasticity, then at maximum amplitude of horizontal vibration, metal density turns out to be the highest. This is also confirmed by the reaction force of the material (tangential force) during indenter passing (scratch method) along the bead crest. Tendency to increase of deposited metal fracture resistance with increase of horizontal vibration amplitude is preserved, while at vertical vibration, it decreases, on the contrary. The large spread of tangential force values shows the low fracture resistance of deposited metal under the conditions of cutting in the presence of fine particles of iron-chromium borides of 10–30 μm^2 in the microstructure of the deposited layers at maximum amplitude of vertical vibration. In the deposited layers produced without vibration, the spread of tangential force values is slightly less than in the deposited metal at vertical vibration. This suggests that under cutting conditions, a larger size of the area (10–150 μm^2) of hard inclusions has a positive effect. At horizontal vibration of 300 μm amplitude, the spread of tangential force values is the smallest, due to a highly homogenous solid solution and small dimensions of hard inclusions. The magnitude of the force of resistance to material fracture increases closer to the zone of overlapping of the deposited layers (Table).

In addition, evaluation of the impact of vibration during surfacing on metal wear resistance was performed by the loss of mass of samples through wear of the deposited surface by fixed and loose abrasive, as well as under shock loading conditions. When testing by fixed abrasive, it was established that for samples deposited without the vibration, the loss amounted to 0.035 g, and at horizontal vibration with the amplitude of 70 and 300 μm it was 0.03 and 0.015 g, respectively. However, at vertical vibration of samples, weight losses increased with increase of vibration amplitude (see Table). The nature of damage of the deposited layers after friction also agrees well with the obtained results of mass wear. At wearing by fixed abrasive, we found fairly deep parallel grooves and traces of crumbled out borides (FeCr)B on the friction surface, produced without vibration (Figure 3, *a*). They easily cracked into pieces, because of friction, and were removed from the contact spot, leaving deep grooves. So, this is what led to low wear resistance of deposited metal.

At horizontal vibration amplitude of 300 μm, there is practically no cleavage from spallation of hypereutectic borides on the surface of the zone of metal contact with abrasive wheel (Figure 3, *b*). However, shallow, nonuniformly distributed traces of friction were observed on deposited layer surface. This is consistent with the nonuniformity of variation of the

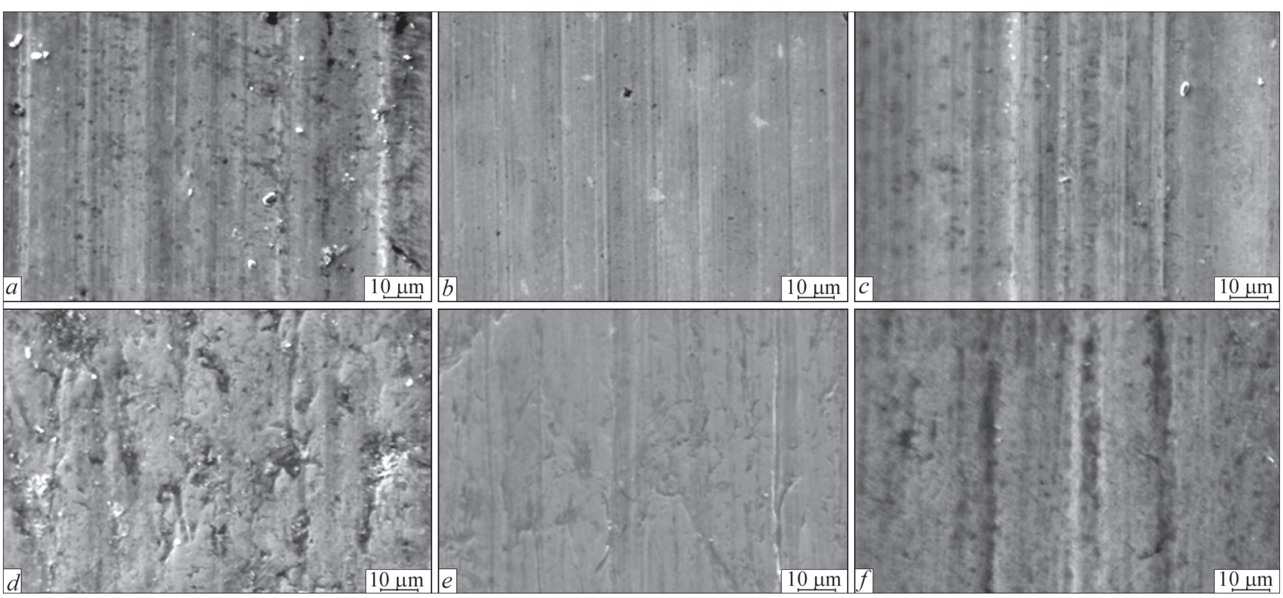

Figure 3. Morphological features of friction surfaces at wear of metal deposited with PP Kh10R4G2S wire without vibration (*a*, *d*) and with horizontal (*b*, *e*) and vertical (*c*, *f*) vibration of samples at 300 μm amplitude, during testing with fixed (*a*–*c*) and loose abrasive (*d*–*e*)

deposited metal microhardness, and presence of soft ferrite matrix grains in the structure. The latter contributes to stress relaxation in the contact zone and, thus, prevents chipping out of hard borides, which exactly cause deep damage of the friction surface.

In the case of surfacing with vertical vibration, deep and wide parallel traces of wear, and traces of chipping out of hypereutectic borides were detected on the friction surface (Figure 3, *c*). Constant increment of wear through deepening of the grooves by boride particles, which in this case acted as microcutters, is, probably, connected with it. Thanks to systematic orientation of borides in the direction of friction, new borides are gradually released from the eutectic matrix as the wheel goes deeper into the material. In this case, they have a negative impact on wear because of the cutting effect. When testing by loose abrasive of layers deposited without vibration, chipping out of hard borides becomes the main wear mechanism (Figure 3, *d*). Here, loose abrasive largely contributes to this chipping out. However, spalled borides leave virtually no characteristic parallel friction traces on the surface. Stiffness of the rubber wheel is, probably, insufficient to create the necessary force of pressing the abrasive to the deposited surface. As a result, spalled parts of borides together with quartz sand are removed from the zone of friction and no longer influence the wearing process. Application of horizontal vibration at surfacing promotes precipitation of inclusions of iron-chromium borides (FeCr)B in the metal structure. They are tightly held by ferritic matrix of FeCr and this makes it difficult to remove them. Therefore, wear is reduced, and shallow dents from ferrochromium boride inclusions and only here and there — grooves formed by them, are observed on the surface.

Study of the influence of vertical vibration on wear by loose abrasive showed that its negative impact persists. Wear surface of deposited layers at vibration amplitude of 300 μm is characterized by numerous traces of hard boride chipping out. Because of local cutting effect, they leave relatively deep grooves on the friction surface (Figure 3, *f*). However, if we compare the reliefs of wear surfaces of the layers deposited without application of vibration and after vertical vibration, it becomes obvious that the determining feature of wear is not the depth of the grooves from friction in the contact zone of the wheel with the metal, but the area of traces and resistance to spallation of hypereutectic borides from the eutectic matrix. Thus, the larger the size of borides and the lower the resistance to their spalling from the matrix, the more intensive is the deposited metal wear, when tested by loose abrasive (Figure 4).

Also analyzed was the nature of damage on the surfaces of bead crests during impact testing. In metal deposited without vibration, significant damage to the crest surfaces was recorded (Figure 4, *a*–*c*), which began as a result of plastic deformation. Violation of cohesive bond between the hard borides and the ductile matrix caused spallation of first coarse, then fine borides, and then separate parts of FeCr matrix (Figure 4, *a*).

Stresses arising in the vicinity of concentrator tips, formed by (FeCr)B-inclusions, were quite sufficient for crack initiation. It is possible that similar cracks can propagate also in-depth the deposited layer, as deposited material hardness was equal to *HRC* 55–57. With longer duration of testing, the density of arrange-

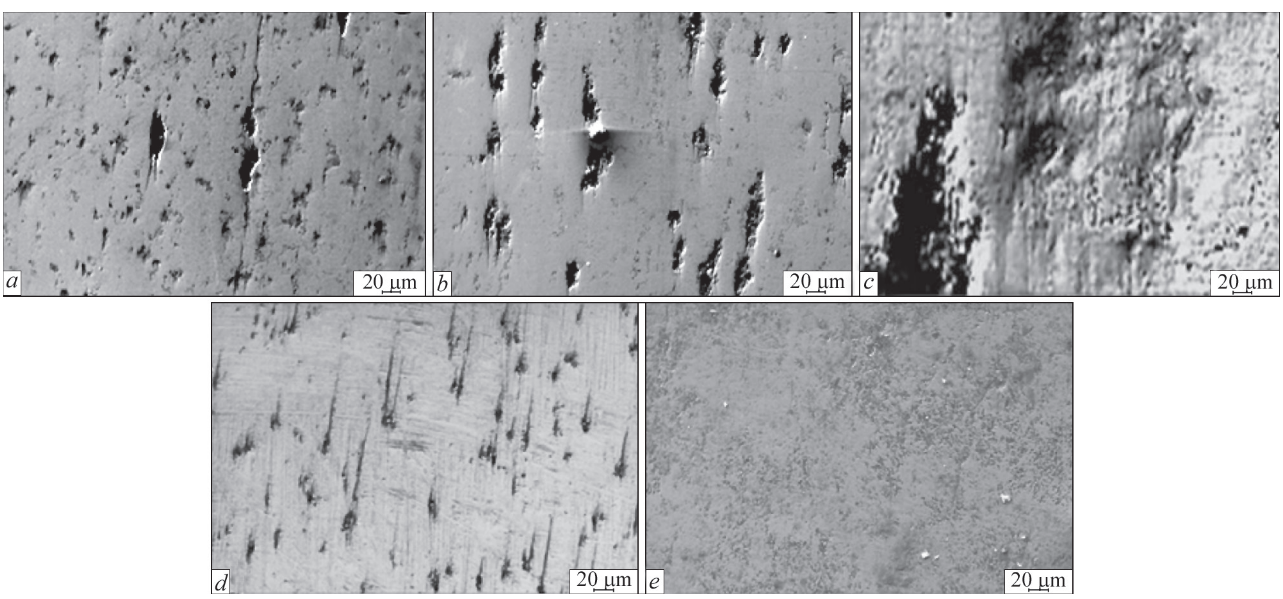

Figure 4. Morphological features of surfaces at application of impact loads: *a*–*c* — without vibration; *d, e* — at vertical vibration; *d, e* — at vibration amplitude of 70 and 300 μm, respectively

ment of sphere impact traces on the surface of the deposited layer became greater. In this case, the partitions between the closest pits were destroyed, releasing coarse (FeCr)B borides from the matrix (Figure 4, *b*). At this stage, fine Fe_2B borides became involved in the fracture. Violation of the cohesive bond with the matrix in them created fine pores in the deposited layer, which contributed to gradual further metal wear (Figure 4, *c*). Here, deep, clearcut pits on worn surfaces of bead crests show the selectivity of the wearing process and its association with larger-sized borides.

Data on weight loss of the samples after impact wear indicate that the use of vibration during surfacing increases deposited layer wear resistance (Table). The features of its influence on damage of deposited metal surface were analyzed. Since at application of vertical vibration with a low amplitude of 70 μm spread of iron-chromium boride area decreased significantly (10–60 μm^2) (see Figure 2, *b*), wear of the surface on bead crest took place by the same mechanism as without vibration. Wear localization was increased, as finer borides were chipped out, the adherence of which to the matrix is significantly stronger. Note the orientation of bands of pits caused by boride spallation, across the weld beads, which is associated with the direction of heat removal during molten pool solidification. As cracking is an effective method of stress relaxation in the deposited layer, the bridges between these pits were easily destroyed (Figure 4, *d*). However, the main contribution to wear was made not by cracks, but by spalled borides. When vibration was used during surfacing, boride area per unit area of the microsection is substantially smaller (see Figure 2, *b*).

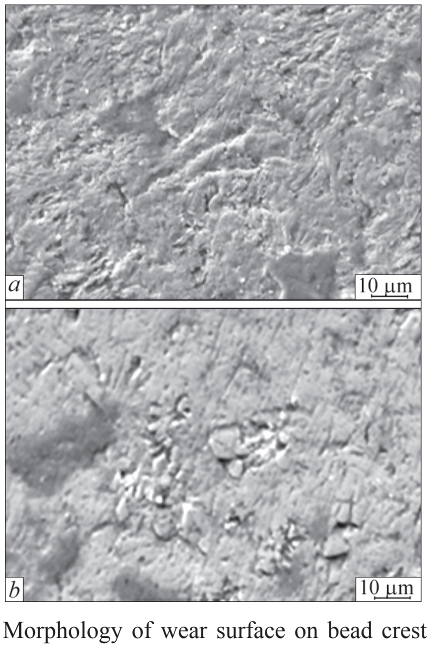

Figure 5. Morphology of wear surface on bead crest in layers, deposited with PP Kh10R4G2S wire, at horizontal vibration of amplitude: *a* — 70; *b* — 300 μm

Therefore, the value of losses from wear should also be reduced. This is consistent with the results of determination of the amount of wear by the weight method (see Table).

At increase of vertical vibration amplitude to 300 μm, signs of general, relatively shallow wear were detected on the bead crest (Figure 4, *d*). This is due to dispersion of strengthening Fe_2B phase. Local wear elements with cracking were observed only occasionally, but these fragments were not the deciding factor. As a special feature, we noted loss of defect orientation that was observed, when other deposition conditions were used. It hinders crack growth at breaking up of the bridges between the pits, and is evidence of a strong cohesion of wear-resistant phases and the matrix.

Application of horizontal vibration changed the phase state and morphological structure of the deposited layer. FeCr rounded grains and dispersed hard particles of iron-chromium borides (FeCr)B appeared. Such structural-phase composition qualitatively changes the nature of the action of load impact. The determinant factor, responsible for metal wear on bead crests, is the ability of the deposited layer to plastically deform, and relax the stresses occurring during impact wear tests. Traces of plastic deformation of deposited metal matrix are a characteristic feature of its surface relief after testing (Figure 5 *a, b*). In the case of bead relief, one can see spallation of its thin layers occurring at later stages of wear, as a result of plastic deformation of deposited metal surface (Figure 5, *a*). As traces of fine impurities were observed underneath them, it can be concluded that the reason for this is the loss of cohesive bond of fine inclusions with the matrix followed by spallation of work-hardened layer from the base (Figure 5).

Wear of weld metal produced at horizontal vibration amplitude of 300 μm occurs by the same mechanism, as at lower vibration amplitude. However, the number of areas where chipping out is promoted by plastic deformation, is reduced, and their localization is increased (Figure 5, *b*). It is typical of metal on the bead crest and is associated with low density of ductile FeCr phase and high dispersity of hard (1.6Fe + 0.4Cr)B phase (cross section of 1–5 μm^2). Note also the lowest cracking susceptibility of surface layers of all the considered variants of deposit formation.

Therefore, the surface layer of metal, obtained using horizontal vibration, is characterized by a high capacity for stress relaxation through plastic deformation and a low cracking susceptibility. This accounts for its high wear resistance in impact tests, which is the result of structural and phase transformations, changes in the morphology and size of reinforcing phases in the structure of the deposited metal.

Conclusions

Microstructure of layers deposited with flux-cored wire PP Kh10R4G2S by automatic submerged-arc process with OSTs45M flux, using vertical and horizontal vibration at a frequency of 100 Hz and vibration amplitude of 70, 300 μm was studied. Application of vibration in the surfacing process provided refinement and rounding of the strengthening (FeCr) B phase.

It is found that the layers deposited at horizontal vibration at the amplitude of 300 μm in bead crest zone, are characterized by high capacity for stress relaxation through plastic deformation of surface layers and a low susceptibility to cracking, that explains their high resistance in impact tests.

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