The connection analysis between the dilution of the deposited Fe-Cr-V-Mo-C layer by the basic metal and the parameters of its microstructure

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Abstract. In this work, the structure of the Fe-Cr-V-Mo-C coatings received by plasma transferred arc cladding was investigated. Coatings were deposited on plates with a thickness of 10 mm and made from constructional steel (steel 20). The correlation analysis of relationships between dilution of the deposited layers by the basic metal and the parameters of their microstructure was carried out. The parameters were as follows: volume fraction, a size, a shape factor, the distance between particles, the number of particles of vanadium carbide, volume fraction of the eutectic on the basis of carbide M_7C_3 and the distances between its colonies, as well as the volume fraction of the α-phase in the alloy matrix.

1. Introduction

Notwithstanding the cladding methods, their regimes should provide the minimum penetration of a processing detail. It provides the preservation of the initial chemical content of a powder composition in the deposited layer. On the other hand, the intention to minimize the dilution of the deposited layers by the basic metal (D) is restricted by necessity of realization of groups of important requirements for coatings. Among these are: the quality of fusion of deposited layers with the basic metal (substrate); the provision of the demanded coatings geometry, the provision of minimum porosity, absence of cracks and ruptures; high efficiency of the cladding process; and the low-loss adding material. For the foregoing reasons, the optimization task of a plasma transferred arc (PTA) cladding regime can be solved exclusively by searching for a compromise solution.

In [1] for the formation of qualitative hard-facing Fe-Cr-V-Mo-C layers, the recommendations for choosing a PTA cladding regime are given. The demand of a limitation of dilution (D) of the deposited layer by the basic metal at a level of 10 % is rooted in the recommendations. However, the reasons of this limitation D are not explained by the authors.

Articles [2-5] underline the necessity of a choice of the cladding regime of the hardened layer taking into account the concrete data about the influence of the regime on its microstructure. The classical orientation to dilution, the macro sizes and the absence of imperfections cannot be universal for all varieties of composite coatings. The realization approach to the choosing of a cladding regime, along with knowledge of its influence on a microstructure, demands labor-intensive research.

The aims of this work are to estimate the correlation force between dilution of the deposited Fe-Cr-V-Mo-C layer, which was generated by the PTA method, and the parameters of its microstructure.

This will allow defining the parameters of a microstructure which demands the individual account for the search of an optimum cladding regime.

2. Materials and experimental procedures

Coating formations were made by the plasma transferred arc welding method, using the UPN-303 standard equipment. The industrial powder 'PR-Cr18VNiMo' (PN-AN2) was used as an adding material. The chemical compositions were (wt. %): 2.1-2.4 C, 17-19 Cr, 2-3 Ni, 7-8 V, 2-2.6 Mo, Fe - the rest. The fraction of the powder was used in the range from 50 to 200 μm. The basic material (substrate) were plates with a thickness of 10 mm. The plates were made of steel 20 (wt. %: 0.17-0.24 C, 0.17-0.37 Si, 0.35-0.65 Mn).

For the coatings production of varied dilutions, two groups of experiments were performed. Group A – cladding without plasmatron lateral oscillation, and group B – cladding with plasmatron lateral oscillation. In experiments of group A – arc current (I) was varied within the limit from 220 to 260 A, cladding speed ranged (V_s) from 4.5 to 13 m/h, the rate of powder feed (V_p) was from 1.1 to 2.2 kg/h. In experiments of group B – arc current was established in a range from 220 to 260 A, V_s equaled 4.5 m/h, V_p was changed in limits from 0.7 to 2.2 kg/h, the peak-to-peak amplitudes of plasmatron oscillation (R) ranged from 10 to 30 mm, and their frequency (v) ― from 0.25 to 0.5 Hz. The working distance between the plasmatron and the item was 10-13 mm, the plasma gas flow rate was 2-3 l/min, carrier gas ― 13-17 l/min and up to 17 l/min of the shielding gas. Argon was used as the enumerated gases. In this paper, microsections preparation was performed in the traditional fashion, through mechanical grinding and mechanical polishing on the diamond paste of various dispersibility.

A microstructure of deposited layers was investigated in section I (figure 1(a)) through the use of an optical inverted microscope, Olympus GX51.
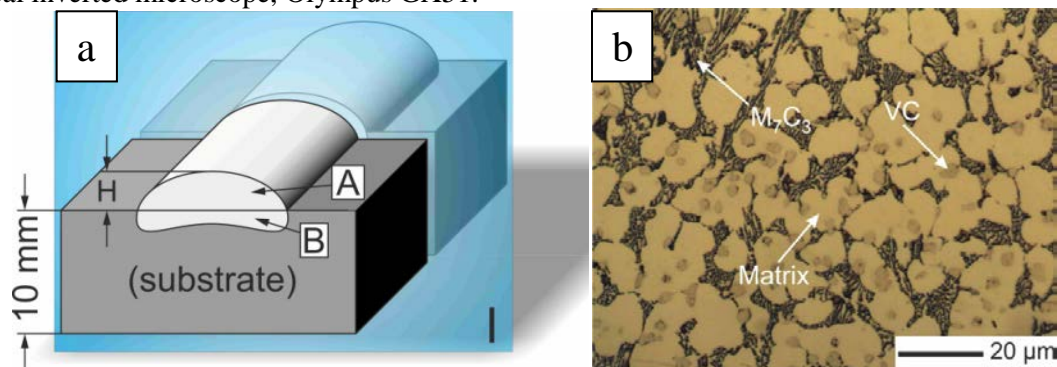
Figure 1. The specimen cutoff scheme (a) and the microstructure of coatings (b).

Macroetching of samples were executed with a 4 % solution of HNO_3 in C_2H_5OH at room temperature during 15-30 s. Dilution (D) was computed according to the following equation [6]:

$$D(\%) = \frac{B}{A+B}100 \;.$$

(1)

In the above-stated equation, B is the area of penetration, mm^2, A is the deposit area without penetration, mm^2.

Particles of vanadium carbide were determined by relief polishing with the following application of microscopy methods: dark-field illumination and differential interference contrast (DIC). To detect eutectic carbide of the M_7C_3 type, the following etching agent was applied: 8.3 g $K_3[Fe(CN)_6]$, 8.3 g KOH, 83.4 ml H_2O. The etching was performed by dipping samples at room temperature for 60-90 sec. Martensite of a matrix was determined by means of a reactant: 20 ml HCl, 1 g $CuCl_2$, 15 ml H_2O, 65 ml C_2H_5OH (etching time from 2 to 20 min). The quantitative analysis of structural elements was performed with application of the analyzer 'SIAMS 700'. The following parameters were measured: the average volume fraction (V_{VC}), the size (d_{VC}, diameter), the number of particles (N_{VC}) related to the

unit of the area of the section (10^4 μm^2), the shape factor (f_{VC}), the distance between particles VC (H_{VC}), the eutectic volume fraction on the basis of carbide M_7C_3 (V_{eut}) and the average distances between its colonies (H_{eut}). The shape factor was computed as a ratio of an orthogonal maximum projection of a particle to the maximum projection of a particle. For the definition of the average rates of parameters under consideration of a microstructure on the transverse microsection from the fusion border to the top, the track of pricks (markers) was pierced by a diamond pyramid with a 300 μm step. To the left and to the right of each marker, a microstructure was analyzed. For an estimation of linear dependences, a Pearson's coefficient of correlation was defined according to the following equation:

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} . \tag{2}$$

In the above-mentioned equation, $\overline{X}$ and $\overline{Y}$ are the arithmetical means of two datasets: $(X_1...X_n)$ and $(Y_1...Y_n)$. Variable X was D, and variable Y was each of the microstructure parameters. Correlation force was estimated according to the Cheddok's scale: $0.1 \leq r_{xy} < 0.3$ – weak correlation; $0.3 \leq r_{xy} < 0.5$ – moderated correlation; $0.5 \leq r_{xy} < 0.7$ – appreciable correlation; $0.7 \leq r_{xy} < 0.9$ – high correlation; $0.9 \leq r_{xy} < 1.0$ – very high (strong) correlation.

In researching the phase composition of coatings, X-ray diffraction analysis was carried out by a Shimadzu XRD 6000 diffractometer with CuK$_\alpha$ radiation in a scan mode in the range of corners 2θ from 30 to 110° with step 0.1°. Well-known card files were used during qualitative phase analysis. Integral intensity rates of the diffractional maximum (111) γ-phase and (110) α-phase were used in the quantitative phase analysis. Hardness of samples was measured by the Rockwell C method (HRC in TK-2M equipment).

3. Results and discussion

The microstructure of the coatings, according to optical microscopy data and X-ray diffraction analysis, consists of disperse particles of vanadium carbide and eutectic skeletal colonies on the basis of carbide M_7C_3 (figure 1 (b)). The matrix in deposited layers is presented by α - and γ - solid solutions (figure 2).
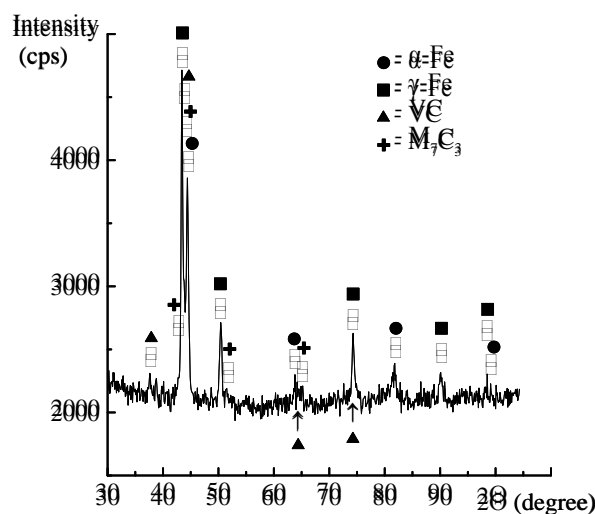
Figure 2. X-ray diffraction pattern of the Fe-Cr-V-Mo-C coating.

In figure 3 (a), there is a dependence of the α-phase volume fraction in the alloy matrix (V_α) on dilution (D). Its analysis allows emphasize 3 characteristic areas for the groups of experiments A and

B. In area I, the α-Fe volume fraction in the matrix decreases from 45 to 20 % with the increase of dilution ($1.5 \leq D \leq 18$ %). In area II ($18 < D \leq 28$ %), V_α does not vary. The further increase of D to 50 % is accompanied by an intense increase of the α-Fe volume fraction in the alloy matrix to 75 %. The difficult nature of communication of the rates is explained by the behavior of two competing processes. The first process is the increasing of the degree of eutectic carbide and vanadium carbide dissolution in a molten pool with the growth of heat input in the work part. As a result, it provides a high content of Cr, V and C in the austenite coating after molten pool crystallization, which greatly reduces martensite start temperature (M_s) and martensite finish temperature (M_f). The second process is the increasing of dilution with an increase of the heat input. It provides the common concentration reduction of doping elements in a coating and, consequently, the rise of the M_s temperature. In the area I, the dissolution process makes a greater contribution to change V_α than the dilution process does. In area II, the dissolution and dilution processes balance each other out, and in area III, the dilution process dominates.
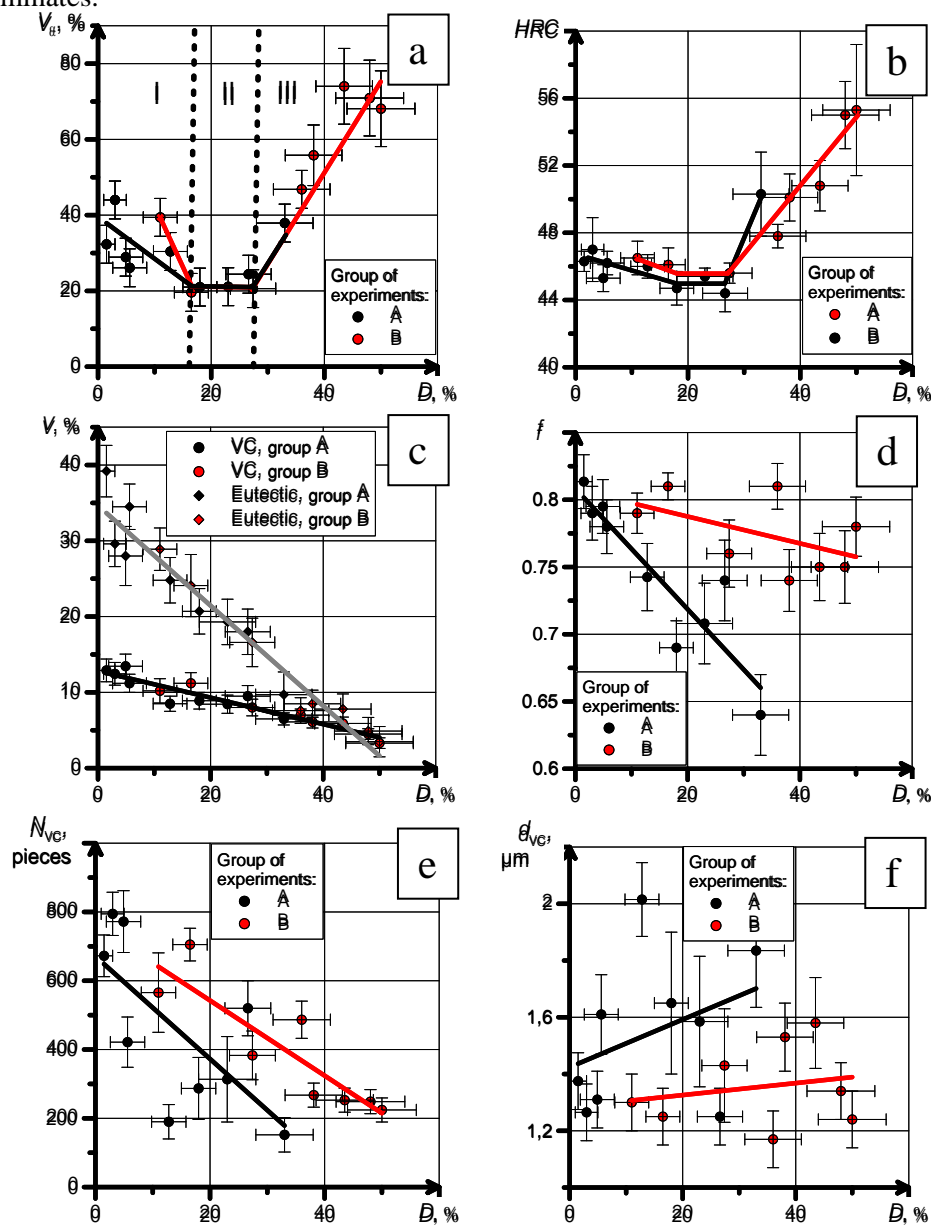
Figure 3. Dependences of V_α (a), HRC (b), V_{VC} and V_{eut} (c), f_{VC} (d), N_{VC} (e) and d_{VC} (f) on dilution (D).

With the D growth, the volume fraction of inclusions of VC and eutectic on the basis of M_7C_3 decreases from 13.5 to 3.5 % and from 39.0 to 3.5 % (figure 3 (c)). This decrease is explained by the two processes described above. The connections of V_{VC} and V_{eut} with D, according to the joint data of experiments of A and B groups, are well described by the first degree polynomials of the following types:

$$V_{VC} = 12.81993838 - 0.1752292615D, \tag{3}$$

$$V_{eut} = 34.66331883 - 0.6607581353D. \tag{4}$$

The intensity of the decrease of an eutectic volume fraction on the basis of M_7C_3 with growth D is considerably higher than the intensity of decrease of V_{VC}. According to the data [7], M_7C_3 is completely dissolved in austenite in the temperatures range of 950-1150˚C. Vanadium carbide is dissolved restrictedly (1.5-2 %) in austenite at 1100-1150 °C. However, in the alloy under consideration, M_7C_3 is less refractory and contains up to 15 % of V. M_7C_3 saturates the hard solution with vanadium in the process of dissolution. In liquid steel it can be dissolved up to 3 % of VC. This information indicates that the reduction of the volume fraction of the eutectic on the basis of M_7C_3 is carried out both at the expense of the dissolution process and the concentration reduction of doping elements in the coating. The V_{VC} reduction occurs mainly at the expense of dilution.

Correlation coefficients take values of 0.95 and 0.97 for the first and the second equations, accordingly. This proves the very high correlation of the VC volume fraction and the eutectic volume fraction on the basis of carbide M_7C_3 with dilution. The equations can be used for prediction of the above-stated parameters of the microstructure coatings, generated by plasma-cladding of powder PR-Cr18VNiMo and other similar Fe-Cr-V-Mo-C alloys. The hardness of deposited layers depends a lot on a α-Fe volume fraction in their matrix (a correlation coefficient is 0.92) (figure 3 (b)).

Figures 3 (d, e, f) and 4 (a, b) present the graphs of dependences f_{VC}, d_{VC}, N_{VC}, H_{VC}, H_{eut} on D, and table 1 shows the estimations of the correlation force. The average diameter of carbide vanadium particles does not depend on dilution. The average shape factor and the average number of VC particles in comparison with V_{VC} and V_{eut} correlates with D comparatively weakly.

Table 1. The estimation of the correlation force of microstructure parameters with dilution (D)

VariableY	Correlation coefficient r_{xy}			The correlation force
	The group of regimes			
	A	B	A+B	
V_{VC}	0.90	0.97	0.95	Very high
V_{eut}	0.94	0.98	0.97	Very high
f_{VC}	0.91	0.52	0.32	Moderated
N_{VC}	0.70	0.88	0.68	Appreciable
d_{VC}	0.33	0.20	0.06	Absent
H_{VC}	0.78	0.89	0.81	High
H_{eut}	0.92	0.92	0.91	Very high

The morphology and the number of vanadium carbide particles are defined by the amount and correlation of C and V in an alloy [8, 9], and by the degree of molten pool supercooling [10, 11]. With the growth of supercooling, the critical radius of a nucleus reduces, as well as the mean diameter of VC particles crystallized from the melt first decreases and the number of particles grows. Also, the disperse VC particles (the diameter is less than 1 μm) which are situated in the adding powder in great numbers (more than 1500 pieces per 10000 μm^2) and which have not been dissolved less in a molten pool coagulate as a result of the decrease of residence time at a high temperature. The shape of VC particles with the growth of supercooling approaches to the equiaxed one. The reduction of the V and

C concentration in a coating as a result of its dilution leads to a decrease of number of VC particles and their elongation. The PTA method allows the formation of the coatings during various thermal cycles. Thus, at the same (D), the degree of molten pool supercooling can vary considerably.

The distances between VC particles and eutectic colonies on the basis of carbide M_7C_3 increased with the growth of dilution (figure 4). Approximating polynomials are the following:

$$H_{VC} = 7.346399084 + 0.2566490277D, \tag{5}$$

$$H_{eut} = 3.232293933 + 0.2928848323D. \tag{6}$$

Correlation coefficients for the first and second equations take values of 0.81 and 0.91. The strength of the positive correlation is high.
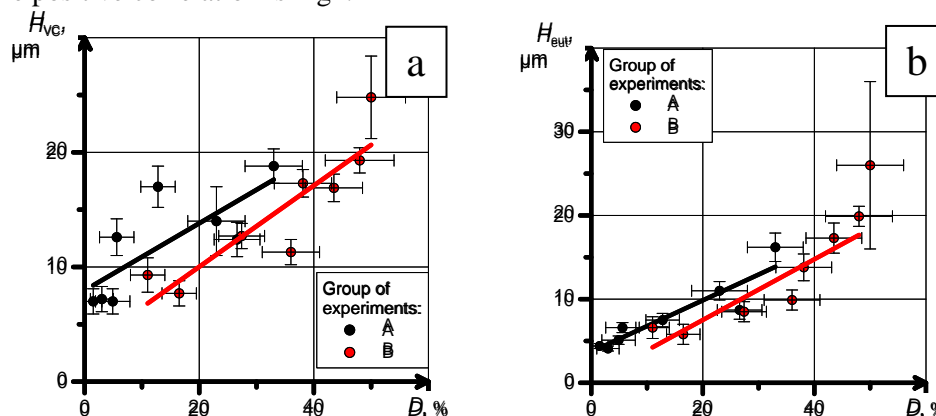
Figure 4. Dependences of the distances between VC particles (H_{VC}) (a) and eutectic on the basis of M_7C_3 (H_{eut}) (b) on dilution (D).

Distinction in correlation coefficients of particle number N_{VC} (0.68) and distance H_{VC} (0.81) with D is explained by changing a matrix's grains size, which mainly has VC spreading along them, as well as by changing this spreading character. With the growth of the dilution, the matrix's grains size increases, the ratio of the number of highly rigid inclusions located along the grains boundary to inclusions located inside of grains grows. The regime of PTA cladding is capable of providing the disperse VC particles obtained in a comparatively great amount even at greater D, however the distance between these particles will be considerable as well.

4. Conclusions
Correlation between the average volume fraction of VC particles or the eutectic volume fraction on the basis of carbide M_7C_3 and the dilution of the deposited layer by the basic metal (D) is linear, negative and very high. Correlation of the average distances between VC particles or eutectic colonies M_7C_3 with D is positive and high. The number, the shape, and the diameter of VC particles, as well as the α-phase volume fraction in a matrix are weakly correlated with the dilution. These rates are defined by a thermal welding cycle. HRC Hardness in the group of alloys under consideration depends a lot on the α-phase's content in their matrix.

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