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FORMATION OF CONTACT INTERACTION ZONES DURING INFILTRATION OF COMPOSITE MATERIALS DEPENDING ON BINDER COMPOSITION

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In the production of macro-heterogeneous composite materials with a metal matrix by the oven infiltration method, it is necessary to control the contact interaction processes occurring at the filler and binder interfaces. The width of the resulting contact interaction zones at the interfaces is an indicator of intensity of these processes. The intensity of contact interaction processes depends on many factors, including the binder alloy composition. The paper examines the effect of binder alloying components on the change in the surface tension of the binder alloy, and, so on the intensity of contact interaction processes occurring at the interfaces during infiltration of composite materials. Calculations of changes in the surface tension of iron-based binder upon alloying with C, P, B and Mo are presented using the formalism of the electrochemical interaction of regular solutions. The iron melt was considered as a solvent, while C, B, P and Mo were considered as dissolved components. It was taken into account that formation of an interface resulted in the appearance of unbalanced charges and energetic influence on the ions distributed in the melt. Adsorption of dissolved components on the filler surface decreased the surface tension of the binder. When estimating the thickness of the layer of excess ion concentration at the surface, we assumed that the binder surface tension depended on the number of adsorbed ions. Our calculations were expressed in accordance with the concept of mole equivalent. It is found that alloying of the Fe–C–B–P binder with Mo causes a decrease in the difference between the surface tension values of the alloyed binder and pure iron melt by 28.5 %, and, accordingly, 22.6 % reduction of thickness of the layer of excess ion concentration. The results obtained were compared with the results of experimental works with regard to composite materials with W–C fillers and iron binders alloyed with C, B, P, and Mo. It is determined that when the Fe–C–B–P binder is alloyed with Mo the width of contact interaction zones in the composite materials decreases by 15–20 %. Therefore, the results of calculations using the proposed method for changing the thickness of the layer of excess ions at the interfaces when alloying the binder correlate with the experimental data for changes in the width of contact interaction zones of composite materials.

***Keywords**: composite materials, binder alloy, surface tension, adsorption, contact interaction zone width*

INTRODUCTION

Composite materials with a metal matrix are increasingly used in the currently available and promising products in the various branches of industrial production [1]. Composite materials with a metal matrix have a number of valuable properties, such as high specific stiffness and strength, fracture toughness, electrical and thermal conductivity *etc*. [2]. Owing to high stability of characteristics of these materials when they are heated up to melting temperatures, they can be used in a wide temperature range [3, 4].

Macro-heterogeneous composite materials obtained by the furnace infiltration method find their application in the industry to create wear-resistant protective coatings [5, 6]. An important condition to ensure the efficiency of this class of materials is strict control of the contact interaction processes occurring at the filler and binder interfaces in the process of the coatings production. Implementation of these processes should, on the one hand, ensure the required strength of interfaces and, on the other hand, prevent the appearance of undesirable phases in the structure [5–8]. Consequently, the filler and matrix interfaces in the metallic composite materials play a decisive role in the securing of the required set of properties [5, 9, 10].

When these composite materials are infiltrated, contact interaction zones of the diffusion-and-dissolution type are formed at the filler and binder interfaces [5, 6]. The width and structure of the above zones characterize the intensity of processes of contact interaction between the filler and the binder during infiltration. Formation of contact interaction zones at the interfaces during infiltration of the composite materials depends on many factors, including the binder alloy composition and quantitative content of components, which alloy the binder [11]. Thus, determination of changes in the width of contact interaction zones of the diffusion-and-dissolution type by changing the alloying elements and their quantity is considered relevant. These characteristic changes in the width of contact interaction zones are determined by experiment. However, in order to identify a certain trend and nature of changes in the width of contact zones on the binder composition, a lot of experimental work is required [5]. Thus, calculation of changes in this characteristic during infiltration of composite materials depending on the composition and amount of the binder alloying elements, without conducting experimental measurements, is a relevant issue.

This paper presents a method for assessing the surface tension of a binder alloy during infiltration of macro-heterogeneous composite materials, as well as changing the thickness of the layer of excess concentration of dissolved ions of the binder at the interface depending on the binder composition and surface tension. The excess concentration gradient is the driving force of formation of a diffusion layer at the interfaces of composite materials during infiltration [12].

The change in the concentration of dissolved ions of the binder at the interface will affect the intensity of contact interaction processes during infiltration of composite materials owing to changes in the surface density of charge. As a result, the overall width of the contact interaction zones of the composite materials formed during infiltration will change. Therefore, it is possible to calculate the change in a given layer thickness based on changes in the binder surface tension, determined by composition of the binder, for the required filler composition and time of infiltration of the composite materials.

The paper presents calculations of the surface tension of binders, as well as changes in thickness of the layer of excess ion concentration at the interfaces of composite materials with the iron-based binder, alloyed with C, B, P, Mo, and reinforced with W – C filler. The calculation data were compared with the results of experimental studies of these composite materials [6].

ASSESSMENT OF CHANGE IN THE WIDTH OF THE LAYER OF ADSORBED IONS ON THE FILLER ALLOY SURFACE DURING INFILTRATION OF COMPOSITE MATERIALS

Now we proceed to calculation of the surface tension of molten binders of composite materials during infiltration. Calculations are made in the CGS system. After calculation, these quantities are converted to the SI system. In the calculations of the change in the surface tension of the given system, we use the formalism of electrochemical interaction of regular solutions. We consider a system where the molten binder is a homogeneous matrix of solvent ions screened by valence electrons. In the absence of an external electric field, this system is electrically neutral one, and dissolved ions that create an unevenly charged ion cloud around themselves can be considered as local disturbances [13].

In order to use the formalism of electrochemical interaction of regular solutions, two conditions stated below should be met:

1. Condition of electrical neutrality of a regular solution, i.e. equality $\sum_a n_{a0} Z_a = 0$ is to be satisfied, where n_{a0} – number of ions in the contact interaction zone per unit volume of the binder, Z_a – positive number reflecting the charge of the a-th ion.
2. Average energy of the Coulomb interaction of two ions should be much less than the average kinetic energy of the ion, i.e. condition $\frac{e^2 Z_a^2}{r} << kT$ should be met, where e – electron charge, $r = n^{-\frac{1}{3}}$ – average distance between ions, k – Boltzmann constant, T – temperature.

The concentration of ions near the interface differs from the concentration in the deep of the molten binder, since there are unbalanced charges at the interface. Formation of an interface causes the appearance of an energetic influence on the ions distributed in the melt, i.e. occurrence of a distribution similar to the Boltzmann distribution

$$\exp\left[-\frac{\omega_a(x)}{kT}\right] \approx 1 - \frac{\omega_a(x)}{kT}\ , \qquad (1)$$

where $\omega_a(x)$ – additional energy of the ion due to the presence of a free surface from which it is at a distance x ($\omega_a(x) \to 0$ at $x \to \infty$).

The content n_s of the dissolved component in the volume of the melt, which is under influence of the energy field of the interface $\omega(x)$, can be represented as

$$n_S = -\frac{SC_a}{\upsilon T}\int_0^\infty \omega(x)dx \ , \tag{2}$$

where S – surface area, υ – molecular volume of the solvent, C_a – average concentration of dissolved compounds in the system.

We use the known relationship

$$n_S = -\frac{\partial\Omega}{\partial\mu_a} = -S\frac{\partial\alpha}{\partial\mu_a} \ , \tag{3}$$

where $\Omega = -PV$, α – surface tension coefficient, μ_a – chemical potential of the dissolved component. Since $\mu_a = T\ln C_a + \psi_a(\mathrm{P,T})$, $d\mu_a = \frac{T}{C_a}dC_a$ we ultimately obtain for the sum of dissolved components

$$d\alpha = \frac{1}{\upsilon}\sum_a dC_a\int_0^\infty \omega_a dx \, . \tag{4}$$

In the environment of the metal melt, the dielectric constant is equal to zero; therefore, the effect of the interface can be expressed as $\omega(x) = \frac{e^2z_a^2}{x}$, then $d\alpha = \frac{e^2}{\upsilon}\sum_a z_a^2 dC_a\int_0^\infty \frac{dx}{x}$ or in the case of one component in the melt

$$d\alpha_a = \frac{e^2z_a^2}{\upsilon}dC_a\int_0^\infty \frac{dx}{x} \ . \tag{5}$$

Now we shall consider the question of the $d\alpha_a$ sign. We can write the relationship

$$n_S = -\frac{\partial\Omega}{\partial\mu} = -S\left.\frac{\partial\alpha}{\partial\mu}\right|_{PV} = -S\left.\frac{\partial\alpha}{\alpha C}\right|_{PV}\left.\frac{\partial C}{\partial\mu}\right|_{PV} .$$

Since $\frac{\partial C}{\partial\mu} > 0$, then in case of positive adsorption $n_S > 0$, the value $\frac{\partial\alpha}{\partial C} < 0$ i.e. adsorption of the dissolved component on the surface reduces the surface tension at the interface.

The function ln*x* diverges at the boundaries of integration specified in (5), so they should be replaced by the real ones. Since we are talking about a filler particle, the lower limit of integration should be compared with some averaged value close to the particle surface. For this parameter, we can use the Debye radius $1/\chi$. The upper limit of integration can be replaced by the distance b, equal to the unit length (1 cm in the CGS system); compared to $1/\chi$ it actually corresponds to ∞. The Debye radius is equal to [13]

$$1/\chi = \sqrt{\frac{kTV_K}{e^2z^2 4\pi N_K}} \ , \tag{6}$$

where N_K – total number of particles in the binder, V_K – volume of the binder element under consideration.

Thus, after integrating over $d\alpha$ and dC_a, we get

$$\alpha = \frac{1}{\upsilon}C_a e^2z^2\left(\ln b - \ln(1/\chi)\right) =$$

$$= \frac{1}{\upsilon}C_a e^2z^2\ln(\chi) = \frac{1}{\upsilon}C_a e^2z^2\left(-\ln(1/\chi)\right), \tag{7}$$

where $b = 1$. It should be noted that under the logarithm sign there is a dimensionless quantity numerically equal to $1/\chi$.

Next, we consider the value of ΔC. Since $\Delta C = C_a - C_{a0}$, where C_a – concentration of the dissolved component near the interface, C_{a0} – average concentration of the dissolved component at a sufficient distance corresponding to the Debye radius $\sim 1/\chi$, this difference can be expressed directly in terms of the values n_a and n_{a0}, where n_a – number of adsorbed particles near the interface in a certain small volume V, n_{a0} – respectively, the number of particles in the similar small volume at a sufficient distance. Further, using a relationship similar to the Boltzmann distribution, we can write the relationship for a distance equal to the Debye radius [13]

$$n_a = n_{a0}\exp\left(-\frac{n_S e^2z^2}{N_{a0}(1/\chi)kT}\right) . \tag{8}$$

Note that the ratio n_S/N_{a0} has been added to the exponent; here n_S – total amount of adsorbed dissolved ions in a thin layer of the interface, N_{a0} – total amount of dissolved ions in the solvent (iron melt) in the entire volume of the melt. This relationship to a certain extent has the nature of normalization, since n_a and n_{a0} is the number of ions distributed, respectively, in the layer determined by the Debye radius. In this case, these quantities will certainly depend on n_S and N_{a0}.

It is assumed that

$$C_a = \frac{n_a}{n_{Fe}} \ . \tag{9}$$

Expanding the exponential function in a series up to the second term, we can write expression (8) as

$$\frac{n_S e^2 z^2}{N_{a0}(1/\chi)kT} = \frac{n_{a0} - n_a}{n_a} \ .$$

Since $n_{a0} - n_a = \frac{n_S}{V}$, we write

$$n_a = \frac{N_{a0}(1/\chi)kT}{Ve^2 z^2} = \frac{n_{a0}(1/\chi)kT}{e^2 z^2} \ . \tag{10}$$

Then, taking (9) into account, we obtain

$$C_a = \frac{m_a \upsilon_{Fe}(1/\chi)kT}{m_{Fe}\upsilon_a e^2 z^2} \ . \tag{11}$$

Substituting C_a into (7), we get for the surface tension

$$\alpha - \alpha_0 = \frac{m_a \upsilon_{Fe}}{m_{Fe}\upsilon_a \upsilon}(1/\chi)kT\left(-\ln(1/\chi)\right), \tag{12}$$

where m_a – weight fraction of the a-th component in the melt, υ_a – molar volume of the a-th component.

It is worth noting that the resulting difference between surface tension of the binder α and surface tension of the pure solvent α_0 will be negative, i.e. alloying elements will reduce the surface tension of the iron-based binder compared to the pure iron melt.

Next, we estimate the number of adsorbed ions near the filler surface n_s in a certain volume. From (2) it follows that

$$n_S = \frac{(\alpha - \alpha_0)S}{kT} = \frac{m_a \upsilon_{Fe}}{\upsilon m_{Fe}\upsilon_a}(1/\chi)\left(-\ln(1/\chi)\right)S \ . \tag{13}$$

The volume near the surface of the filler containing adsorbed ions n_S is estimated. In a first, rather rough approximation, this value can be estimated from the relationship

$$V \approx \frac{n_S}{n_{a0}}, \tag{14}$$

since n_{a0} has the dimension of concentration, when we do not take into account changes in the distance between adsorbed particles in relation to dissolved ones in the entire volume.

Hence the approximate width of the layer of excess ion concentration near the surface

$$l \approx \left(\frac{n_S}{n_{a0}}\right)^{1/3} = \left(\frac{\pi \upsilon_{Fe}(1/\chi)^3\left(-\ln(1/\chi)\right)}{\upsilon m_{Fe}}\right)^{1/3} , \tag{15}$$

where $n_{a0} = \frac{m_a N_A}{\upsilon_a}$, $S \approx \pi(1/\chi)^2 N_A$, N_A – the Avogadro's number. The contact area is calculated per mole of the substance. The value $\pi(1/\chi)^2$ represents the area normalized to one particle of dissolved component of the substance, since the Debye radius itself is formed by one particle of dissolved substance. Therefore, to express the whole area equivalent to system units (in this case the mole) it should be multiplied by the Avogadro's number.

It is advisable to determine the l dimensions at the melting temperature as a value that determines the point of reference when we find the comparative characteristics. This value can be considered as the initial condition when solving equations. In the further calculations, the l dimension at a certain temperature will be found as the difference between the values of this quantity at a given temperature and at the melting temperature.

Components in the melt have different valences, which, from the standpoint of the traditional chemistry, requires a certain normalization in relation to valence. It follows from considerations of the formalism of diluted solutions, which are essentially the melts under study. The relationship of the form $\Delta P = \frac{nkT}{V}$, similar to the Van't Hoff equation, is typical for the diluted solutions, where n – content of the dissolved compound in molar terms without taking into account the charge determined by the valence electrons, P – pressure. From this point of view, it makes sense to express our calculations in accordance with the concept of mole equivalent, which is further implemented in our conclusions.

Therefore, thickness of the layer of excess concentration of the binder alloy ions formed at the surface of the interfaces in composite materials will depend on the surface tension of the binder and the temperature. Consequently, it is possible to assess the impact of the composition of binder alloying elements on the formation of contact interaction zones at the interfaces during infiltration of composite materials. We can also evaluate the change in the thickness of the layer of excess concentration of melt ions near the surface of the filler depending on the temperature.

EXPERIMENTAL TECHNIQUE

Composite materials were produced by the furnace infiltration method at a temperature of 1180 °C for 30 min [6]. The eutectic Fe–3 %C–1.8 %B–1 %P alloy (alloyed with molybdenum in amount of up to 0.5 wt. %) was used as a binder, while W–3.7 %C eutectic alloy granules of microcrystalline structure manufactured by the method of thermo-centrifugal spraying of the rotating rod [14] were taken as a filler. Structure of these materials was studied using the quantitative metallographic, X-ray diffraction and micro-X-ray spectrum analyses. To measure the width and relative content of phases in the structure of contact interaction zones between the filler and the matrix, an original statistical method was used in addition to the metallographic research method [15].

RESULTS AND DISCUSSION

Macro-heterogeneous iron-based composite materials are characterized by high operational resistance due to reinforcement with refractory filler particles, as well as the use of the wear-resistant binder alloy [16]. For example, iron-based materials, which contain the W – C eutectic alloy as a refractory filler, are promising for the wide application as the protective coatings on parts of metallurgical and mining equipment [16]. However, disadvantage of these alloys is their active interaction with reinforcing particles of tungsten carbides at high infiltration temperatures [17]. As a result, undesirable brittle phases appear in the structures of the iron matrix – filler interfaces, which reduce the performance of the materials [6]. The intensity of contact interaction processes during infiltration can be additionally reduced by lowering the melting temperature of the Fe–C binder by introduction of boron, phosphorus and molybdenum into its composition [6].

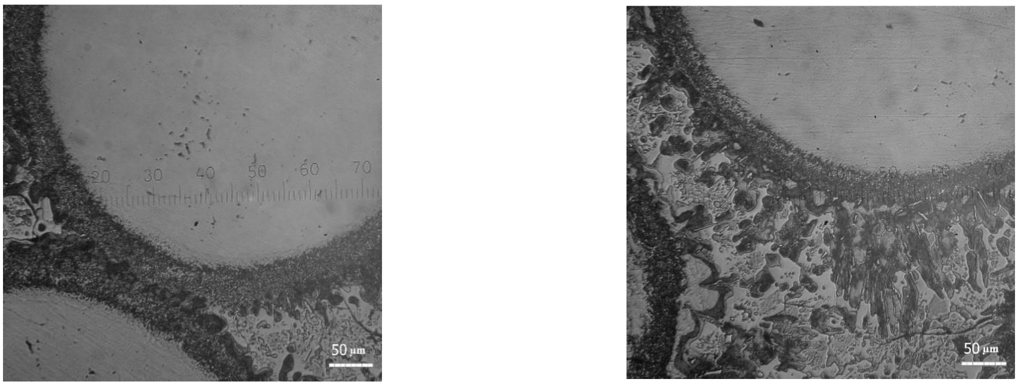
To test the above hypothesis about the effect of thickness of the layer of adsorbed ions of the binder alloy on the surface of fillers on the intensity of processes at the interfaces and, accordingly, on the formation of width of the contact interaction zones, we selected the Fe–3 %C–1.8 %B–1 %P/W–3.7 %C alloy and molybdenum-alloyed Fe–3 %C–1.8 %B–1 %P – 0.5 %Mo/W–3.7 %C alloy. Therefore, the effect of alloying Fe–3 %C–1.8 %B–1 %P binder alloy with 0.5 % Mo on the change in contact interaction processes at the interfaces of composite materials during infiltration was considered.

All calculated values of the surface tension and thickness of the adsorption layer, normalized in mole equivalents for these binders are given in Table. It is assumed in the calculations that melting temperature of the Fe–3 %C–1.8 %B–1 %P binder is ~ 50 K lower than the infiltration temperature; it is also taken into account that alloying with Mo additionally reduces the melting temperature by ~ 5 K [18]. The calculation of mole equivalents of dissolved components was reduced to a total volume of the binder of $1.5\cdot10^{-5}$ m^3. As can be seen from table, introduction of 0.5 % Mo into the Fe–3 %C–1.8 %B–1 %P binder alloy reduces the difference in surface tension by 28.5 %, i.e. as a result of such alloying the binder surface tension increases, and, accordingly, thickness of the layer of excess ion concentration decreases by 22.6 %.

Table. Values of the difference between the surface tension of binders and thickness of the adsorption layer at the interfaces of Fe–3 %C–1.8 %B–1 %P/W–3.7 %C and Fe–3 %C–1.8 %B–1 %P – 0.5 %Mo/W–3.7 %C composite materials

	$1/\chi$, m	**$\alpha - \alpha_0$, N/m^2**	***l*, μm**	**$\alpha - \alpha_0$, N/m^2, reduced to mole equivalent**	***l*, μm, reduced to mole equivalent**	**Average width of contact interaction zones, μm**
Fe–C–B–P binder	$9.06\cdot10^{-12}$	0.02547	53	0.04892	103	96
Fe–C–B–P–Mo binder	$8.66\cdot10^{-12}$	0.02563	56	0.03807	84	79
Change, %				28.5	22.6	21.5

As a result of experimental studies [6], it was found that after infiltration the granules of spherical fillers evenly distributed in the hardened binders were observed in the structures of materials (Fig. 1). The average size of filler granules is 525±16 μm, and the filler volume content is ~ 60±8 vol. %. It is found that contact interaction zones are formed at the filler – matrix interfaces. On the filler side, in addition to the eutectic of WC – W_2C near the interfaces there is a layer of WC monocarbide and Fe_3W_3C phase. On the matrix side, inclusions of the Fe_3W_3C phase are present in the eutectic structures of Fe – $Fe_3(C,B)$, alloyed with carbon compared to the original structure.

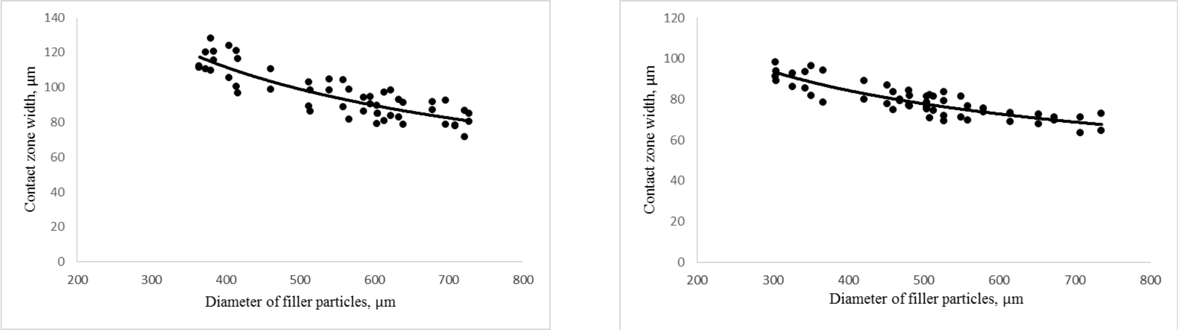


a *b*

Fig. 1. Microstructure of composite materials, ×400: *a* – Fe–C–B–P binder; *b* – Fe–C–B–P–Mo binder

The results of determining the relative content of these phases using the statistical method showed that in the composite materials with Fe–C–B–P–Mo binders the relative content of α-Fe+ $Fe_3(C,B)$ eutectic and crystals of W_2C in the contact interaction zones increased compared to composite materials with Fe–C–B–P binders. While the content of crystals of Fe_3W_3C и WC decreases, there is also no precipitation of the decomposed austenite phase.

Measurements of the width of contact interaction zones showed that in composite materials with the Fe–C–B–P–Mo binders this characteristic is reduced by an average of 15–20 % compared to composite materials with the Fe–C–B–P binders (Fig. 2, Table).



a *b*

Fig. 2. Dependence of the width of contact interaction zones on the diameter of spherical particles of the filler: *a* – Fe–C–B–P binder; *b* – Fe–C–B–P–Mo binder

It follows from findings [6] that alloying with Mo of the Fe–C–B–P binder alloy of the composite materials strengthened with tungsten carbides causes a decrease in the intensity of contact interaction processes during infiltration, as well as the width of contact interaction zones, which is a positive result.

Comparison of experimental results with the data of calculations shows that changes in the width of contact interaction zones and thickness of the layer of excess concentration of binder alloy ions near the surface of the fillers correlate with each other. In addition, the presented method for calculation of changes in the thickness of the layer of excess ion concentration found a certain correlation with other experimental data [5]. For example, for (Cr–Ti–C)/(Fe–3.1 %B–1 %C) alloy the thickness of the excess concentration layer increased significantly with the temperature rise. This fact is similar to experimental data [5].

Thus, the values calculated with the use of the proposed method for estimating the thickness of the layer of excess ion concentration at the interfaces of composite materials, formed during infiltration, correlate with experimental data for changes in the width of contact interaction zones. Therefore, using this method, it is possible to approximately estimate by calculations the effects of alloying components of the binder alloy on the intensity of contact interaction processes and formation of contact interaction zones at the interfaces of composite materials during infiltration. This circumstance can be used to solve the applied problems in the manufacturing of macro-heterogeneous composite materials without conducting of experimental studies.

CONCLUSIONS

The paper presents a method for quantitative assessment of the change in surface tension of the binder alloy of composite materials due to alloying of the binder. The molten binder was considered as a homogeneous matrix of solvent ions screened by valence electrons of the ions of dissolved elements. The formalism of electrochemical interaction of regular solutions was used in the calculations.

Considering this fact, we determined the content of dissolved component in the volume of the melt, which was influenced by the energy field of the interface.

Using the proposed method, quantitative assessments were made of the changes in the surface tension of the binder and thickness of the layer of excess concentration of dissolved ions due to alloying of the Fe–C–B–P binder with molybdenum.

The results of calculation of changes in the thickness of the layer of excess concentration of dissolved binder ions on the filler surface correlate with experimental data for changes in the width of contact interaction zones at the interfaces of W–C/Fe–C–B–P composite materials alloyed with molybdenum.

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Формування зон контактної взаємодії при просоченні композиційних матеріалів в залежності від складу зв’язки

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При отриманні макрогетерогенних композиційних матеріалів з металевою матрицею способом пічного просочення необхідно здійснювати контроль процесів контактної взаємодії, що відбуваються на межі поділу між наповнювачем та зв’язкою. Ширина зон контактної взаємодії, що утворюються, на межі поділу є показником інтенсивності цих процесів. Інтенсивність процесів контактної взаємодії залежить від багатьох факторів, у тому числі від складу сплаву-зв’язки. В роботі досліджено вплив легуючих зв’язку компонентів на зміну поверхневого натягу сплаву-зв’язки, і відповідно на інтенсивність процесів контактної взаємодії, що відбуваються на межі поділу при просоченні композиційних матеріалів. Наведено розрахунки зміни поверхневого натягу зв’язки на основі заліза при легуванні C, P, B та Mo, використовуючи формалізм електрохімічної взаємодії регулярних розчинів. Розплав заліза розглядали як розчинник, а C, B, P та Mo як розчинені компоненти. Враховували, що утворення поверхні поділу викликає появу незбалансованих зарядів та *енергетичного впливу на розподілені у розплаві іони. Адсорбція розчинених компонентів на поверхні наповнювача знижувала поверхневий натяг зв'язки. При оцінці товщини шару надмірної концентрації іонів біля поверхні приймали, що від кількості адсорбованих іонів залежить поверхневий натяг зв'язки. Проведені розрахунки виражали відповідно до поняття моль-еквівалент. Отримано, що легування Мо зв'язки Fe–C–B–P викликає зменшення різниці поверхневого натягу легованої зв'язки та чистого розплаву заліза на 28.5 %, і відповідно зменшення товщини шару надлишкової концентрації іонів на 22.6 %. Отримані результати порівнювали з результатами експериментальних робіт для композиційних матеріалів з наповнювачами W–C і залізними зв'язками, легованими C, B, P і Mo. Визначено, що при легуванні Мо зв'язки Fe–C–B–P ширина зон контактної взаємодії в композиційних матеріалах зменшується на 15–20 %. Таким чином, результати розрахунків запропонованим методом зміни товщини шару надлишкової концентрації іонів на межі поділу при легуванні зв'язки корелюють з експериментальними даними зміни ширини зон контактної взаємодії композиційних матеріалів.*

Ключові слова*: композиційні матеріали, сплав-зв'язка, поверхневий натяг, адсорбція, ширина зон контактної взаємодії*

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