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Original article

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Content and Dispersion of Ferroalloys in the Coating During Microarc Alloying of Steel

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Abstract

Introduction. The main disadvantage of traditional processes of diffusion surface hardening of steel products is its long duration. Therefore, the problem of intensification of such processes is relevant. To solve it, the use of high-energy effects on the material is proposed, which allows us to obtain a hardened surface layer from a coating composed of ferroalloy powders containing alloying elements. There is no data in the literature on the required content and dispersion of such powders in the composition of the coating. The aim of this study was to select the particle size of ferroalloys and their concentration in the coating to achieve the most effective hardening of the processed product.

Materials and Methods. For experimental studies, cylindrical samples made of steel 20 with a diameter of 12 mm and a length of 35 mm were used. On the surface of these samples, an alloying coating containing ferroalloy powders and an electrically conductive gel as a binder was applied. After that, the samples were immersed vertically for half their length into a metal container, which was then filled with carbon powder with a particle size of 0.4–0.6 mm. Then an electric current of 2.5 to 3.0 A was passed in the circuit power source — container — carbon powder — sample. The duration of the process was 2–8 minutes.

Results. The calculated estimation of the electrical conductivity of coal powder was performed, and the thermophysical parameters of microarc heating of steel were calculated. These include the power released by electric current on the surface of the steel product, the density of the heat flux, and the energy of a single microarc discharge. The expressions for calculating the particle size of ferroalloy powder were obtained, as well as the experimental dependencies of the diffusion layer thickness on the particle size of ferroalloys and their content in the coating.

Discussion and Conclusion. The results of this study have allowed us to determine the size range of ferroalloys and their content in the coating. This information is essential for optimizing the alloying process and ensuring the most efficient surface hardening treatment for steel products. The data collected will be used to develop improved technological processes for the surface hardening process, leading to improved product quality and performance.

Keywords: chemical-thermal treatment, microarc energy, diffusion saturation of steel

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Научная статья

Содержание и дисперсность ферросплавов в обмазке при микродуговом легировании стали

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Аннотация
Введение. Основным недостатком традиционных процессов диффузионного поверхностного упрочнения стальных изделий является большая продолжительность, поэтому проблема интенсификации таких процессов является актуальной. Для ее решения предложено применение высокоэнергетического воздействия на материал, позволяющего получить упрочненный поверхностный слой из обмазки, в состав которой входят порошки ферросплавов, содержащие легирующие элементы. В литературе отсутствуют данные о необходимом содержании и дисперсности таких порошков в составе обмазки. Цель исследования — выбор размера частиц ферросплавов и их концентрации в обмазке для достижения максимально эффективного упрочнения обрабатываемого изделия.
Материалы и методы. Для экспериментальных исследований использовали цилиндрические образцы из стали 20 диаметром 12 мм и длиной 35 мм, на поверхность которых наносили легирующую обмазку, содержащую порошки ферросплавов и электропроводный гель в качестве связующего. После этого образцы погружали вертикально на половину длины в металлический контейнер, который далее заполняли угольным порошком с размером частиц 0,4–0,6 мм. Затем пропускали электрический ток величиной от 2,5 до 3,0 А в цепи источник питания — контейнер — угольный порошок — образец. Продолжительность процесса составляла 2–8 мин.
Результаты исследования. Выполнена расчетная оценка электрической проводимости угольного порошка, рассчитаны теплофизические параметры микродугового нагрева стали: мощность, выделяемая электрическим током на поверхности стального изделия, плотность теплового потока, энергия единичного микродугового разряда. Получены выражения для расчета размера частиц порошка ферросплавов, а также экспериментальные зависимости толщины диффузионного слоя от размера частиц ферросплавов и их содержания в обмазке.
Обсуждение и заключение. Результаты исследования позволили определить диапазон размеров частиц ферросплавов и их содержание в обмазке, позволяющие обеспечить наиболее эффективное легирование поверхности обрабатываемых изделий. Полученные данные будут использованы при разработке технологических процессов поверхностного упрочнения стальных изделий.

Ключевые слова: химико-термическая обработка, энергия микродуги, диффузионное насыщение стали

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Introduction. The duration of various processes of chemical-thermal treatment (CTT) of steel can reach 8–10 hours [1, 2]. Therefore, methods of their intensification based on the application of high-energy effects on the material using plasma heating [3], electro-chemical-thermal treatment [4], combined heating methods [5] laser treatment [6], microarc oxidation [7], and heating in an electrolyte [8] were previously proposed. However, these methods are difficult to apply in practice and therefore have not been widely used. To intensify the CTT processes, it is advisable to use microarc surface alloying, which allows you to achieve a significant (tenfold) acceleration of diffusion saturation process, and does not require the use of complex equipment. A special feature of this method is the immersion of the processed product with a coating applied to its surface in carbon powder. Then an electric current is passed through them. The intensification of the saturation process is achieved due to the formation of diffusant ions and their subsequent accelerated diffusion into the material under the influence of electric and temperature fields. In previous studies, positive results have been achieved using this method for diffusion saturation with chromium, molybdenum, vanadium [9], and tungsten [10]. For complex saturation, a coating was pre-applied to the surface of the processed product, which included a ferroalloy powder containing a diffusant. These studies made it possible to determine the structure and phase composition of the coatings obtained, but the task of achieving the maximum hardening efficiency, which requires determining the optimal particle sizes of ferroalloy and its content in the coating, was not set in previous studies.

The aim of the study was to determine the conditions for the most effective hardening of steel products by microarc alloying due to the choice of particle sizes of ferroalloy powders and their concentration in the coating used.

Materials and Methods. For experimental studies, samples of steel 20 containing 0.2 wt. % C with a diameter of 12 mm were used, on the surface of which a coating prepared on the basis of an electrically conductive gel with the addition of ferroalloy powders was applied. The samples were immersed vertically for half their length in a metal container with a diameter of 35 mm, which was then filled with coal powder with a particle size of 0.4–0.6 mm. Then an electric current of 2.5 to 3.0 A was passed through the sample for 2–8 minutes.

To prepare the coating, powders of ferrochrome, ferromolybdenum, ferrovanadium, ferrotungsten with a particle size of 0.40–0.50 microns and a binder in a volume ratio of 1:1 were used.

The samples were polished according to the standard procedure, followed by etching with Rzheshotarsky reagent. The microstructure of the diffusion layer was studied using a Neophot–21 microscope.

To measure the bulk density of coal powder, the methodology according to GOST 3258-2013 was used. The powder was dispersed by particle size using a set of sieves according to GOST 33 029-2014.

Results. The bulk density of coal powder, i.e. the mass of a unit volume of freely poured powder, was determined experimentally, the values obtained are shown in Figure 1.

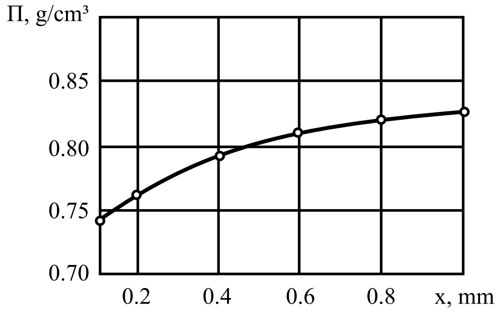

Fig. 1. Dependence of bulk density П of coal powder on size X of its particles

In the size range from 0.4 to 0.6 mm, the average bulk density could be assumed to be 0.81 g/cm^3. The obtained value made it possible to determine the volumetric density of coal powder as the ratio of bulk density to the density of coal, the value of which was borrowed from reference literature [11] and assumed to be 1.6 g/cm^3, from where the volumetric density was assumed to be 0.81/1.6=0.51. The obtained value approximately corresponded to the packing density of a simple cubic lattice (0.52). Therefore, according to [12], it could be assumed that the total resistance of the powder medium was the sum of the resistances of successive layers consisting of parallel chains of the contact resistance RK between the particles and the resistance RM of the particles themselves (Fig. 2).

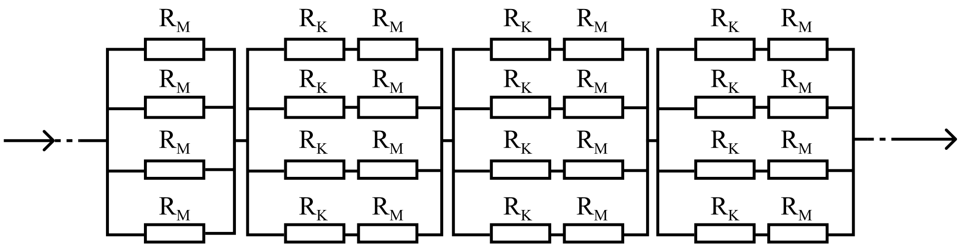

Fig. 2. Electrical contacts of carbon particles in the powder medium:
R_K — resistance of interparticle contacts;
R_M — resistance of a single carbon particle

Calculation according to Figure 2 allowed us to estimate the total electrical resistance R of the powder medium:

$$R = \sum_{m=0}^{n} \frac{(R_K + R_M)d^2}{2\pi H(r + dj)}, \tag{1}$$

where m — number of layers of carbon particles; r — radius of the sample; d — diameter of the particles; H — depth of immersion of the sample; R_K — resistance of interparticle contact; R_M — resistance of a single carbon particle. The following values were used for calculations: $d = 0.5 \cdot 10^{-3}$ m, $H = 1.5 \cdot 10^{-2}$ m, r = 6 mm, R_K = 6 kOhm, R_M = 0. Value R was assumed to be 15.5 Ohm. The obtained value allowed us to calculate: electric current power $P = I^2R$, energy of a single microarc discharge Q_0, surface current density f, heat flux density q. Value Q_0 was defined as the ratio of the current power to the total number of microarcs that simultaneously affected the heated surface for 1 second. According to the video recording, value M was assumed to be 22,500. Table 1 provides the calculation results.

Table 1

Values of thermophysical parameters of microarc heating

I, A	$f\,10^{-2}$, A/cm^2	$P\cdot10^2$, W	$q\,10^5$, W/m^2	$Q_0\,10^{-3}$, J
2.5	45	0.97	1.71	4.3
2.75	49	1.17	2.07	5.2
3.0	53	1.39	2.47	6.2

Next, the maximum size d_{max} of a ferroalloy particle was calculated, for the vaporization of which the energy of one microarc was sufficient.

The required amount of heat Q, taking into account specific heat of sublimation λ, can be written as: $Q = \lambda m$, where m — mass of the particle.

For a spherical particle with density ρ:

$$m = \rho V = \frac{1}{6}\rho\pi d^3 .$$

Therefore, the desired condition has the form:

$$\lambda\rho\pi d^3 / 6 \le Q_0 .$$

The maximum particle diameter required to fulfill this inequality:

$$d_{max} = \sqrt[3]{\frac{6Q_0}{\lambda\pi\rho}} . \quad (2)$$

Calculated d_{max} values are shown in Table 2.

Table 2

Calculation results

Ferroalloy		Fe+Cr	Fe+Mo	Fe+V	Fe+W
d_{max}, mm	0.45 A/cm^2	0.045	0.043	0.044	0.038
	0.49 A/cm^2	0.048	0.046	0.047	0.040
	0.53 A/cm^2	0.050	0.048	0.050	0.042

Thus, it was established that the maximum particle size of ferroalloys used in the coating composition should not exceed 38 microns.

The thickness of the diffusion layer was experimentally determined depending on the volume fraction of ferrochrome particles in the coating and its thickness. To do this, ferrochrome powder FKh010A with a particle size of 40–50 microns was added to the binder in the amount necessary to obtain its volume content in the range of 10–50%

Figure 3 provides the results. It can be seen that the maximum coating thickness was formed at a volume concentration of ferrochrome particles in the coating of 50% and its thickness of 0.5 mm. Thus, the maximum intensification of the diffusion saturation process was achieved under the condition of the highest content of ferroalloy particles in the coating, and the ferroalloy particles adjacent to the saturated surface must be exposed to microarcs.

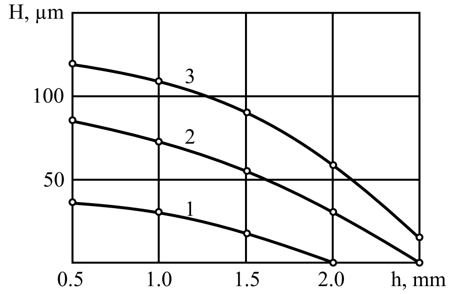

Fig. 3. Dependence of depth H of the hardened layer on thickness h of the coating layer for different contents of ferrochrome powder (vol. %) in the coating: 1 — 10; 2 — 30; 3 — 50

Discussion and Conclusion. Calculated assessment of electrical conductivity of coal powder used for microarc alloying of steel products made it possible to establish the influence of the magnitude of electric current in the circuit on thermophysical parameters of the process: the density of the heat flux on the heated surface, the power released on the heated surface, the energy of a single microarc discharge occurring between the heated product and the surrounding powder medium during the flow of electric current. The results obtained made it possible to determine the diameter of ferroalloy particles used for microarc alloying, their volume fraction in the coating, which ensure the achievement of the greatest intensification of microarc alloying process. The research results will be used in the development of technological processes for surface hardening of steel products by microarc surface alloying.

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Claimed contributorship:

MS Stepanov: calculations of electrical parameters of the powder medium and thermophysical parameters of microarc heating, analysis of the results.

YuM Dombrovskii: experimental studies, determination of technological parameters of the microarc surface alloying process, analysis of the results.

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