Influence of plasma arc power on the melting of the envelope layer containing NiCrBSi alloy and the surface coating quality during plasma heating

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Abstract. The experiments are carried out to obtain coatings by plasma heating of an envelope containing a NiCrBSi alloy with different thicknesses (0.25; 0.5; 1.00 mm) on exposure to different powers (100; 140; 160 A). The resulting coatings have different depths of the hardened layer. With a thin preliminary envelope layer (0.25 and 0.5 mm), defects easily appear under the influence of high power. With a thicker envelope layer (1 mm), the ability of the alloy to diffuse into steel is limited. The low power of the plasma arc of 100 A limits the diffusion and transformation of the molten pool, sufficient for saturation with alloying elements of a thick layer of the envelope (0.5 and 1 mm).

1. Introduction

It is known that under operating conditions carbon steel is faced with factors affecting its quality, such as corrosion, wear, erosion and other mechanical influences. Among the methods for improving the quality of metals, alloying of the surface of metals has contributed to improving the operability and service life of metallic materials. Nickel and chromium based coatings are widely used in various industrial sectors [1]. Many coating methods are popular, for example, chemical, electrochemical deposition and the use of highly concentrated sources. Electrochemical and electrochemical deposition coatings have a more uniform coating or can be easily covered with multiple coats with little impact on the inner layer and are also highly corrosion resistant. However, they have thin thicknesses (about hundredths of a micrometer), even in these methods, water waste is harmful to the environment. Due to stringent requirements for surface preparation before processing, to obtain coatings requires many stages and is time-consuming, with relatively low hardness [2-4].

The combination of chromium and nickel has been repeated many times in a number of studies [5-8]. However, to obtain a protective coating that simultaneously increases the hardness and corrosion resistance, the use of nickel-based alloys (NiCrBSi, NiCrB, NiCr) and the use of a highly concentrated source are considered suitable, since the composition contains not only corrosion-resistant elements, such as Ni, Cr, Si, but also elements that increase the hardening of Ni, Cr, Si, B [4-9]. To overcome
some of the disadvantages when using popular highly concentrated sources, such as the cost of equipment in laser overlay weldings [10, 11]; the presence of porosity from a few percent, relatively low adhesion, low productivity with thermal spraying [10-12], electric arc surfacing (TIG) under protective gas is used in many studies [12-14]. In addition, the use of a preliminary envelope layer, as in traditional methods of chemical thermal treatment (CTT) [13-16], recommending a thickness of no more than a millimeter can help increase the efficiency of using molten materials.

We have successfully obtained high-quality cemented coatings by the TIG method with an envelope layer thickness less than a millimetre [16, 17]. In studies [18, 19], the authors used polyvinyl alcohol as a binder forming the applied coating with a thickness of less than 1 millimetre. Plasma treatment with various modification mixtures containing the PR-N80Kh13S2R alloy [19] with thin layers of envelopes showed that a better coating quality was formed with than with thick ones. In other works [16, 17, 20] it is shown that the use of silicate glue or water glass to prepare thin layers of the envelope brought better quality coatings. The presence of silicon in the glue increases the self-fluxing ability of the envelope; the silicate glue prevents the alloy from contrasting with air [16, 17, 20]. Many studies using the TIG method consider a wide range of plasma arc power, as for example when working with a current of 60 – 190 A [16, 17].

The purpose of this work is to evaluate the quality of the coating of the NiCrBSi system during plasma heating of mixtures of various envelope thicknesses, including powder alloy PR-N80Kh13S2R and silicate glue with plasma arc current powers (100, 140, 160 A).

2. Materials and methods of study

Plasma heating was carried out after applying the paste on the surface of Steel 3 (St3) and drying the sample. The chemical composition of St3 consists of C (0.14-0.22%), Si (0.05-0.17%), Mn (0.4-0.65%), Ni, Cu, Cr (≤ 0.3%), As (≤ 0.08%), S, P (≤ 0.05%). Powders are used to prepare the paste: alloy PR-H80H13C2R with granules of 40 – 100 microns; glue (silicate); the chemical composition of the PR-H80H13C2R alloy is shown in table 1:

| C (%)  | Si (%)  | Cr (%) | B (%) | Ni (%) | Fe (%) | HRC  |
|-------|---------|--------|-------|--------|--------|------|
| 0.2-0.4 | 2.0-2.8 | 12-14  | 1.2-1.8 | The other | ≤ 3    | 25-35 |

Figure 1. Paste layer manufacturing and plasma treatment scheme.
The order of applying the coating of the experiment is presented in Figure 1. The paste mixture of powder alloy and glue was applied on the surface to obtain a relative thickness of the envelope of 0.25 – 0.50 – 1.00 mm after drying. Plasma modes were: current of 100, 140, 160 A; argon consumption was 10 l/min; the gap between the tungsten electrode and the part is 5 mm; the speed of sample movement is 2.7 mm/s.

The samples after plasma treatment were prepared for metallographic research and microhardness measurement. Before studying the microstructure, samples were etched in a 2% solution of nitric acid in ethyl alcohol. The microstructure was observed with the electro-microscope MET-2. The microhardness measurement was carried out on the hardness testing device of the NMM-G series.

3. Results and discussion
The sample cross-section microstructure types with the resulting coatings are shown in Table 2. We can see that with a thickness of 0.25 mm, all coatings are saturated with alloying agents at different processing capacities. At the same time microfractures occur at 140, 160 A, and there is none of them at 100 A. With a thickness of 0.5 mm, at 100 A the alloy is not completely melted down with the main metal, but forms various sublayers in the hardened surface layer. Using a higher power, for a coating thickness of 0.5 mm, the alloy is melted down with the base metal, but cracks appear again at 160 A. There are no cracks and pores in the coatings of a series of samples with a 1 mm thickness of the envelope layer, but different zones are formed, even chaotic ones. The depth of the surface modified layer at different thicknesses of the smear is presented in Figure 2.

It is obvious that the use of different thicknesses of the envelope and 3 different capacities leads to a strong change in the depth of the resulting coatings. The thicker the layers of pre-applied envelopes, the stronger the mixing down with the main metal at the modes of one power, because of the higher power there is a stronger dilution of the main steel metal with the same thickness of the envelope. High power provides heat transmission sufficient to dissolve alloy powder and support plate in the molten pool and full saturation. Due to this, solid (martensitic) phases are quickly formed, but defects (cracks) also quickly appear during cooling.

The difference in surface layer cooling speeds between plasma treatment with natural cooling and plasma treatment with additional cooling in water may be the cause of this problem. Thicker preliminary layers, for example, 1 mm, significantly prevent the conversion of part of the main steel into a solid solution, leaving enough volume for the NiCrBSi alloy saturation process. It can be seen that in these coatings the boundaries of molten pool surfacing and support plate are uneven, with unevenly distributed sublayers, there appear small areas of saturated phases inside unsaturated areas and, on the contrary, in the microfractures of the saturated sublayer, filled with flows of unsaturated phases.

It is possible to say that coatings No. 1, 3 are of higher quality, corresponding to the modes of: 100 A and 0.25 mm, 140 A and 0.5 mm thick coating (Figure 3). Coating No. 2, corresponding to a 0.5 mm thick envelope and a power of 100 A, has various sublayers: the upper one is lighter, the lower one is darker. The distribution of the microhardness values of the coating No. 2 showed that a large difference between the upper and lower sublayers is due to the unsaturated part of the alloy containing the austenite-forming element Ni, i.e. the power is not enough to distribute heat into depth from the surface of the sample (Figure 2).
**Table 2.** Plasma coating cross-section types.

| Envelope thickness | Power 100 A | Power 140 A | Power 160 A |
|--------------------|-------------|-------------|-------------|
| 0.25 mm            | ![Depth is 1250 μm](image) | ![Depth is 1240 μm](image) | ![Depth is 1560 μm](image) |
| 0.25 mm            | ![Depth is 1150 μm](image) | ![Depth is 1300 μm](image) | ![Depth is 1810 μm](image) |
| 1 mm               | ![Depth is 1470 μm](image) | ![Depth is 1630 μm](image) | ![Depth is 2020 μm](image) |

**Figure 2.** Dependence of the depth of the alloyed layer on the power and thickness of the envelope.
Figure 3. Distribution of the microhardness values of the cross-section of samples along the depth from the surface of the coatings.

Figure 4 shows the distribution of microhardness values along the depth from the surface of coatings No. 1, 3. It can be seen from the graph that sample No. 1 has a large difference in hardness between the main coating and the heat affected zone (HAZ), and the microhardness values of the base metal do not differ much from the HAZ zone. In the sample No. 3, the initial values of hardness vary in depth within the range of 400–480 HV, and further in depth, closer to the boundary of the overlay welding bath, it significantly increases within the range of 530–570 HV. In particular, when passing to the HAZ zone, the hardness decreases slowly, even further areas of the base metal are also higher than that of coating No. 1. The difference in the distribution of hardness shows that the parameters of the power of the plasma arc significantly affect the coating quality in terms of the distribution of hardness and phase structures along the layer depth. To clarify the process of coating formation, Figure 5 shows the mechanism.

In the case of only the melting of the NiCrBSi alloy, it is possible to describe the coating formation mechanism in several steps. In the first step (A), a dried layer of envelope containing a mixture of NiCrBSi alloy and glue (liquid glass) is applied to the surface of the metal. In the second step (B), a high heat flow from the plasma arc partially heats the layer of envelope, and its upper part is melted down as a liquid (partially solid alloy solution is formed during crystallization). In the 3rd step (C), the whole layer of the envelope is melted down in the form of liquid. In the 4th step (E), part of the steel support plate, close to the edges of the envelope, interacts with the liquid. At the same time, the intersecting part of the solid alloy solution starts passing into a steel solution. In the last step (G),
parts of the solid alloy solution and steel are mixed together. After cooling, different zones are formed, presented in the type of cross-section (table 2). In general, the coating has 2 sublayers, respectively with the types of zones: the top is the molten alloy; the middle is the mixed saturated sublayer of alloy and steel. The lower part of the surface layer forms a heat affected zone.

![Figure 4](image-url). Distribution of the microhardness values along the depth from the surface of the coatings.

4. Conclusion
Coatings of different thickness of the NiCrBSi alloy envelope layer at different plasma arc powers show that:

- With a thin preliminary layer of envelope (0.25 and 0.5 mm) under the influence of a high-power plasma arc, defects occur easily, and with a thicker layer (1 mm) the ability of alloy to be diffused in steel is limited because of the small dissolution of the main metal, which is not enough for the full saturation of the alloy. The small power of the plasma arc by the current intensity of 100 A limits the diffusion and in the small volume of the molten pool, which is not enough for the full melting of the thick layer of envelope (0.5 and 1 mm).

- Microstructure research and micro-solids measurement have shown that coating No.1 corresponding to 0.25 mm thickness, 100 A and No. 3 (0.5 mm, 140 A) are better than the rest of them.

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