Structure formation of high-temperature alloy by plasma, laser and TIG surfacing

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Abstract. The paper presents the results of a study of the formation of the structure and properties of metals in the technologies of additive processes, namely plasma, arc and laser surfacing of high-alloy Chromium-Nickel alloys. The main problem of Chromium-Nickel alloys in the processing of highly concentrated energy sources (welding, surfacing, soldering, plasma and laser processing) is insufficient strength and heat resistance after high heating and rapid cooling, characteristic of these methods. The paper presents the results of a study of the structure, phase formation and properties of Chromium-Nickel alloys in plasma surfacing of high-alloy steel wire. To study the possibilities of modifying the structure during argon-arc surfacing, additional ultrasonic action on the deposited material was applied with the help of a waveguide connected to the lower surface of the sample. A comparison of the structures of the surfacing alloy obtained by laser cladding found that arc welding of alloy in combination with ultrasonic action created the additional effect of increasing the dispersion of the phases, which led to increased high-temperature strength of the alloy.

1. Introduction

TIG, plasma and laser surfacing are one of the most effective technologies for additive manufacturing, combining the wide technological possibilities for obtaining complex products with a unique complex of mechanical and special properties of the material, including high-alloy Chromium-Nickel alloys.

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One of the basic principles of the theory of alloying of high-temperature alloys adopted in metallurgy is the principle of multicomponent alloying, aimed at nanostructuring the heterophase structure of alloys. The structure of the alloys that belong to the Ni-Cr-Ti-Al system is the γ- solid solution and the γ'- phase (intermetallides Ni3(Ti, NiAl) + Nb, Mo, W carbides). Multicomponent alloying of the γ- solid solution and γ'- phase is carried out in such a way as to ensure high phase and structural stability of the alloy. When a certain ratio between the total content of Al, Ti (γ'-forming elements) and the total content of Mo, Cr (mainly γ- stabilizing elements) is reached, the maximum hardening and stability of the structure are ensured. At the same time, the material contains particles of the γ'- phase of different sizes, formed by a complex thermal treatment, including quenching and aging [1-3]. The presence of Ti and Al in these alloys in amounts exceeding their ultimate solubility in a solid solution at temperatures of 650-950 °C makes it possible to achieve a significant effect of
dispersion hardening after quenching and tempering, owing to the separation of dispersed particles of the intermetallic phase of Ni₃(Ti, NiAl) type. Such a microstructure makes the alloy stable against the temperature influence at 700-800 °C or higher.

Introduction to the dispersion-hardening alloys of this group W and Mo (up to 10% in total), as well as Nb, further strengthens the solid solution, slows the development of diffusion processes and increases the amount of dispersed strengthening phase. The amount of dispersed phase is also increased by increasing the total content of Ti and Al. All this leads to a significant increase in the heat resistance of alloys, which makes it possible to use them at temperatures up to 800-850 °C and high stresses.

The highest heat resistance of these alloys is achieved after quenching and subsequent aging, resulting in the formation of fine-grained precipitates of the γ'-phase, which inhibit plastic deformation.

A typical microstructure of a heat-resistant Chromium-Nickel alloy is shown in figure 1: a homogeneous field of the γ- solid solution, particles of the γ'- phase of Ni₃(Al, Ti), 0.05-0.3 μm in size, and a chain of complex carbids Me₂₃C₆, MeC through all the fields of the microsection.

However, the achieved level of heat resistance of nickel alloys is often significantly reduced as a result of thermal influence and unfavorable structural changes in subsequent processing methods (welding, surfacing).

The paper presents the results of investigating the structure, phase formation and properties of high-alloy Chromium-Nickel alloys of the EP648 type with TIG, plasma and laser surfacing.

![Figure 1. Microstructure of the heat-resistant Chromium-Nickel alloy Cr15Ni55Co17Mo5Al4Ti3B after solution heat treatment and two-fold aging (840 and 760°C for 24 hours), ×30000 (ASM) [8].](image)

2. Technologies, research methods and materials

The chemical composition of the investigated alloys is given in table 1.

Plasma surfacing on a nickel alloy EP 648 was produced with a wire EP 609 at a BPS-350 type installation (development of PNRPU).

The following parameters of the regime were varied: current 100 - 240 A; voltage 18 - 24 V; protective gas - CO₂ and N₂; polarity - straight and reverse; the speed of movement of the plasmatron -20 cm/min.
Figure 2. Plasma surfacing by a plasma arc with a neutral filler wire: 1 – protective nozzle, 2 – plasma forming nozzle, 3 – protective gas, 4 – plasma-forming gas, 5 – electrode, 6 – power supply, 7 – wire, 8 – sample.

Table 1. Chemical composition of nickel alloys, wt %.

|            | CrNi50WMoTiAlNb (EP 648) | CrNi65WMoTiAl | 07Cr12NiMoNbV (EP 609) |
|------------|---------------------------|---------------|------------------------|
| C          | ≤0.1                      | ≤0.05         | ≤0.09                  |
| Si         | ≤0.4                      | ≤0.6          | ≤0.6                   |
| Mn         | ≤0.5                      | ≤0.5          | ≤0.3                   |
| Cr         | 32-35                     | 15-17         | 10-12                  |
| Ni         | base                      | base          | 1.4-1.8                |
| Ti         | 0.5-1.1                   | 1.2-1.6       | -                      |
| Al         | 0.5-1.1                   | 1.2-1.6       | -                      |
| W          | 4.3-5.3                   | 8.5-10.0      | V 0.15-0.25            |
| Mo         | 2.3-3.5                   | 3.5-4.5       | 0.3-0.5                |
| Nb         | 0.5-1.1                   | -             | 0.05-0.15              |
| Fe         | ≤4.0                      | ≤3.0          | base                   |
| B          | ≤0.008                    | ≤0.01         | -                      |

TIG surfacing was carried out on plates of alloys 10 mm thick on an installation with an inverter power supply, the Scheme of which is shown in figure 3. The TIG surfacing was carried out according to the regime given in table 2.

Figure 3. Scheme of the process of TIG surfacing with additional ultrasonic treatment of Chromium-Nickel alloys.
Table 2. TIG welding mode.

|                          |       |
|--------------------------|-------|
| Welding current, A       | 120   |
| Argon consumption, l/min | 7     |
| Feeding speed, mm/min    | 200   |
| Frequency of ultrasonic influence, kHz | 22 |
| Distance from the sample to the cut of the burner nozzle, mm | 10 |

To investigate the possibilities of modifying the structure, an additional ultrasonic action was applied to the deposited material by means of a waveguide which led to the lower surface of the plate. The distances to the places where the samples are cut from the point of application of the ultrasonic action are given in Table 3.

Table 3. Distances to the point of application of ultrasonic action for TIG surfacing.

| Sample № | L, µm |
|-----------|-------|
| 1         | 60    |
| 2         | 50    |
| 3         | 30    |
| 4         | 15    |
| 5         | 0     |

* Sample №1 – TIG surfacing without ultrasonic influence

Laser surfacing on the TruLaser Cell 7020 (figure 4) was carried out in argon. The powder was fed in helium.

Figure 4. Scheme of the head of the laser surfacing installation with the powder feeding system.

Table 4. Laser surfacing mode.

|                          |       |
|--------------------------|-------|
| Laser power, W           | 750   |
| Diameter of the laser spot, mm | 1.3 |
| Feeding speed, mm/min    | 120   |
| Duration, ms             | 35    |
| Frequency, Hz            | 5     |
| Powder consumption, g/min| 3     |
| Note                     | Pulse mode |

The flow rate of argon and helium is 7 and 4 l/min, respectively. Laser surfacing was carried out according to the regime given in Table 4. Surfacing is performed in 5 tracks of 3 layers with pauses for cooling between the aisles. Before surfacing, the thermal treatment was carried out at a temperature of 1130 °C ±10 °C, holding for 3
hours. After surfacing, thermal treatment in vacuum (10⁻⁵ mm Hg) at a temperature of 1000 °C ±20 °C, holding for 2 hours was carried out.

Quantitative metallographic analysis was carried out on an automated complex of image analysis and modeling of structures VideoTest-metal.

The volume fraction of the pores in the cladding was determined using the ThixometPro program in a cell with a size of 1 mm² of the section area at 100 times magnification.

Fractal parameterization of structures was carried out by MATLAB software using the technique [4].

3. Result

3.1. Plasma and TIG surfacing on Chromium-Nickel alloy EP 648 with wire EP 609

When depositing dissimilar materials, the boundary layer is of greatest interest from the standpoint of structural strength. The presence of such a layer with increased hardness and, obviously, a lower relaxation capacity in the structure can serve as a prerequisite for the appearance of cracks already in the process of crystallization. Both methods of surfacing are characterized by a sharp increase in the microhardness in the boundary layer (figure 5): in the plasma layer it is almost 2 times higher than in the base (up to 440-450 HV), while for TIG surfacing it is lower - up to 400 HV.

![Figure 5. Microhardness in the depth of metal during plasma and TIG surfacing on nickel alloy EP 648 with wire EP 609, ×300.](image)

The metal of the plasma surfacing is characterized by a more dispersed structure (figure 5). TIG surfacing forms a coarse structure with large dendrites having almost rectilinear boundaries. This structure is extremely unfavorable, since it has an increased tendency to hot cracks. Figure 6 shows cracks in real products with TIG surfacing.

In addition, it is established that the plasma effect leads to an increase in the purity of the surfacing for nonmetallic inclusions of the oxide and sulphide groups. Figure 7 shows a typical distribution of inclusions in size groups in the fusion zones for plasma and TIG surfacing. It was revealed that with TIG surfacing the share of large inclusions of 9-10 size groups (20 μm and higher) grew, the largest accumulation of inclusions was in the overheating zone. On average, the level of metal contamination with TIG surfacing is higher by 20-30% compared to the metal of the plasma surfacing, regardless of the current strength and polarity.
4. TIG surfacing on nickel alloy EP 648 with additional ultrasonic action
Decrease of running energy and additional ultrasonic influence helps to reduce the defectiveness of metal and the tendency to form hot cracks in the argon-arc surfacing. It was established that argon-arc surfacing of the EP648 alloy with an ultrasonic effect created an additional effect of an increase in the fineness of the $\gamma'$ phase (figure 8), which led to an increase in the microhardness of the alloy.

The high value of microhardness (up to 250 mm/kg$^2$) corresponds to surfacing with the location of the ultrasonic source at a distance of 25-30 mm, which, obviously, is optimal by this criterion. Cracks and porosity under the optimal surfacing regime are not fixed the combined curves of the dependences of the volume fraction of the $\gamma'$ phase in the structure and microhardness of the deposited layer from the distance to the focus of the ultrasonic action in the argon-arc surfacing of the EP648 alloy are shown in figure 9.

Figure 9 shows the dependence of heat resistance on the grain size of Chromium-Nickel alloys, formed on the basis of analysis of research papers [5, 6] for similar alloys in composition. It follows from figure 10 that the highest heat resistance (up to $\sigma_{100700} = 700-750$ MPa) is possessed by Chromium-Nickel alloys with a fine-grained structure (score not less than 6-7).
Figure 8. Microstructure of metal TIG surfacing of alloy EP648 with ultrasonic action and without it, ×300.

Figure 9. Dependence of the volume fraction of the γ'- phase in the structure and microhardness of the deposited layer from the distance to the focus of ultrasonic action for argon-arc surfacing of EP648 alloy.

Figure 10. The dependence of heat resistance on the grain size of Chromium-Nickel alloys [5, 6].
Comparison of these data with the results of our studies allows us to conclude that the combination of favourable structural parameters - fine-grained $\gamma$-solid solution and increased dispersion of the $\gamma'$-phase, which is realized in TIG surfacing with additional ultrasonic action at optimal conditions, leads to an increase in microhardness and heat resistance of Cr-Ni alloys.

**Table 5.** Structural parameters, microhardness and heat resistance of nickel alloy EP648 under TIG surfacing depending on the distance to the focus of ultrasonic action.

| Distance from the source of ultrasonic action, mm | Fractal dimension of the $\gamma'$-phase, D | Microhardness, HV | Mark of grain $\gamma$-solid solution | Estimated level of heat resistance |
|-----------------------------------------------|-----------------------------------------|------------------|-------------------------------------|----------------------------------|
| 0                                            | 1.01                                    | 210              | 6                                   | 600                              |
| 20                                           | 1.03                                    | 205              | 7                                   | 700                              |
| 30                                           | 1.06-1.08                               | 249              | 7-8                                 | 700-750                          |
| 40                                           | 1.01                                    | 235              | 6                                   | 600                              |
| 60                                           | 1.02                                    | 230              | 6                                   | 600                              |

The mechanism of the influence of ultrasonic radiation on the effect of modifying the structure of the deposited layers can be explained using certain positions of the theory of diffusion, and also taking into account the analogous results obtained in the investigations [7] for coating and welding. The application of ultrasonic action for surfacing Ni-Cr-B-Si-C alloys intensifies the diffusion processes of alloying elements, and also increases the mobility of the grain boundaries [7]. This, in turn, contributes to the refinement of the grains of the $\gamma$-solid solution based on nickel, and to a more even distribution of the $\gamma'$-phase. The structure formed by ultrasonic treatment hinders plastic deformation in the welded layers and leads to an increase in the mechanical properties and heat resistance of the surfacing and welded joints.

5. **Laser surfacing of the alloy EP648 on the alloy VJL14**

The structures of surfacing of chromium-nickel alloy obtained by laser surfacing are compared. For comparison, figure 11. The structure of laser surfacing of the alloy EP648 on a sample of the alloy VJL14 is shown. The total height of the deposited layers on all sections is 1.6 mm. The depth of the zone of thermal influence on all samples is 0.12 mm.

**Figure 11.** Microstructure of laser surfacing EP648 on a sample from alloy VJL14 (cracks are indicated by red arrows).

High porosity is characteristic of laser surfacing. The results of the evaluation are shown in table 5. The microsections show that there are cracks in the surfacing material in sections 1 and 2.
The results of evaluating the porosity of the laser surfacing material had a volume fraction of pores: 0.76-0.96%; the maximum pore size is 75-85 μm. The microhardness in the surfacing layer was 216-222 HV. The purity level of laser surfacing was slightly lower than in plasma surfacing.

Thus, with laser surfacing of similar materials, the worst results of defectiveness and the level of material properties are observed.

6. Conclusions
1. It was found that plasma exposure of Chromium-Nickel alloys leads to increased purity of surfacing for non-metallic inclusions of oxide and sulfide groups. On average, the level of metal contamination during TIG surfacing on the weld on EP 648 nickel alloy by EP 609 wire is 20-30% higher compared to the metal of the plasma surfacing, regardless of the current and polarity.
2. When surfacing dissimilar materials (surfacing a nickel alloy EP 648 with EP 609 wire), a transition layer with an increased microhardness is formed up to 1.5-2 times in comparison with the substrate, which can lead to the formation of hot cracks.
3. It was found that argon-arc surfacing of nickel alloy EP 648 in combination with additional ultrasonic action creates a modifying effect of increasing the phase dispersion.
4. The combination of favorable structural parameters - fine-grained γ- solid solution and increased dispersion of γ'- phase, which is realized under argon-arc surfacing with additional ultrasonic action at optimal conditions, leads to an increase in the microhardness and heat resistance of nickel alloys.
5. Laser surfacing of Chromium-Nickel alloys yields worse results both in terms of defectiveness and material properties. In the surfacing material, porosity is present in all sites, the volume fraction of pores at the place of maximum porosity reaches 0.96%.

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