Structure formation of titanium alloys during vacuum-arc surfacing

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Abstract. The work is based on wire vacuum-arc surfacing as one of the technologies for additive manufacturing. The results of the formation of structure and properties of a high-temperature titanium alloy of the Ti-Al-V-Mo-Zr system during vacuum-arc surfacing are presented. The structure of the surfaced materials consists of dendritic grains that are oriented in the direction opposite to heat removal. Some banding of the structure is observed. There is no porosity in the deposited layers for all surfacing modes. It was determined that a decrease in the surfacing current promotes an increase in the dispersion of the α-phase plates, which is accompanied by an increase in microhardness. With such a thermal cycle of surfacing, conditions are created for the formation of a favorable fine-dispersed martensitic structure with narrow α-colonies of small needles of the α-phase, providing a high microhardness at the level of 400HV.

1. Introduction

The use of additive arc processes makes it possible to synthesize large-sized parts with a minimum allowance for machining and provide mechanical properties of metal at the level of traditional technologies, allows to obtain significant savings in metal and significantly reduce the cost of technological preparation for production [1-7]. The work considers wire-arc surfacing in vacuum as one of the technologies for additive manufacturing.

At the preliminary stage of research, it was revealed that significant disadvantages of titanium alloys in surfacing technologies are unfavourable dendritic structure, anisotropy, banded structure and, as a consequence, a decrease in mechanical properties (for example, the ultimate strength \( \sigma_u \)) is below 850 MPa, in particular, the loss of plasticity [8-11].

The purpose of this work is to study the main regularities of the structure formation and properties, as well as the influence of the main surfacing parameters (arc current, filler wire feed rate) on the geometric characteristics of the deposited beads of the heat-resistant titanium alloy (Ti-Al-V-Mo-Zr system) during wire vacuum-arc surfacing.

2. Materials and technology

Surfacing was performed using a 1.2 mm titanium alloy filler wire. The chemical composition of the filler wire is shown in Table 1.

| Element | Content, wt. % |
|---------|----------------|
| Al      | 5.5...7.0      |
| V       | 0.8...2.5      |
| Mo      | 0.5...2.0      |
| Zr      | 1.5...2.5      |
| Si      | < 0.1          |
| Fe      | < 0.3          |
| C       | < 0.1          |
| N       | < 0.05         |
| O       | < 0.15         |
| Ti      | 85.15...91.4   |
| H       | < 0.015        |

This alloy is based on the ternary system Ti-Al-V, which is typical for the majority of high-strength titanium alloys that belong to pseudo-α-alloys. In accordance with the principles of heat-resistant alloying of titanium alloys, the multicomponent alloy is alloyed with α-stabilizers (Al), β-stabilizers (V, Mo, Fe, Zr) and neutral hardeners (C, N). This provides an effective combination of dispersion and solid solution hardening mechanisms.

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Surfacing was performed with use of equipment designed in Perm National Research Polytechnic University. The process scheme is shown in Figure 1.

![Process scheme](image)

**Figure 1.** Schematic of vacuum-arc surfacing process: 1 – welding torch; 2 – product (anode); 3 – plasma-forming gas valve; 4 – CNC coordinate table; 5 – wire feed mechanism; 6 – filler wire

The process was implemented using a hollow cathode torch (1) with tungsten WL-15 electrode with 1 mm inner cavity diameter. To ensure the conditions for the formation of an arc discharge with a hollow cathode, a micro flow of argon was supplied through the cavity with use of a plasma-forming gas valve (3).

3. **Results**

   To determine the effect of surfacing mode parameters on the structure and properties of the deposited material cross-sections of the deposited beads were studied. The external view and cross-sections of the deposited beads are shown in Figure 2.

   ![External view and cross-sections](image)

   **Figure 2.** External view (left) and cross-sections (right) of the titanium alloy beads obtained by vacuum-arc surfacing

Table 2 shows the parameters of the surfacing modes and the average values of the deposited layer parameters: height \((h)\), width \((b)\) and the microhardness \((HV_{0.1})\).
Table 2. Parameters of vacuum-arc surfacing modes and average values of deposited beads parameters

| № | Arc current $I$, A | Deposition rate $V_d$, mm/s | Wire feed speed $V_f$, m/min | Deposited bead height $h$, mm | Deposited bead width $b$, mm | Microhardness Interval $HV_{01}$ | Average $HV_{01}$ |
|---|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1 | 150           | 3.5             | 3.5             | 0.97            | 5.70            | 225...416      | 340             |
| 2 | 150           | 3.5             | 3.2             | 0.98            | 5.41            | 265...457      | 349             |
| 3 | 120           | 3.5             | 2.5             | 0.91            | 4.48            | 372...441      | 407             |

The macrostructure of the surfacing materials is dendritic and oriented in the direction opposite to heat removal. Structural banding is observed. There is no porosity in the deposited metal for all processing modes.

Analysis of the microstructure of the deposited material was carried out in different areas of the deposited bead (Fig. 3).

![Image](image1.png)

Figure 3. Microstructure of individual sections of the deposited bead: $a$, $b$ – central part, $c$ – fusion line

The base metal has the typical structure of a titanium alloy in a deformed state: grains elongated in the rolling direction, which are rather long fibers. A change in the structure in the fusion zone is clearly visible: elongated grains of the rolling structure are replaced by an equiaxed, not very coarse grains near the fusion line and larger dendrites in the center of the surfacing. A transcrystalline dendrite adjustment has been marked, which is typical for titanium alloys. The phase composition of the deposited metal has a small amount of the initial $\beta$-grains (in fact, it is guessed only by thin interlayers along the grain boundaries), colonies of $\alpha$-plates of various sizes with intragranular plates of the martensitic $\alpha'$-phase of different thicknesses. The deposited metal is also characterized by different fineness of the $\alpha$-colonies plates, and the size of individual needles of 1...100 µm. This difference in the morphology of the structure is explained by the different cooling rates during crystallization and by the stage of solid state transformations.

With low cooling rate, a lamellar structure is formed, represented by colonies of almost parallel $\alpha$-plates with a microhardness not higher than 360 HV. It was found that a decrease in the current during arc surfacing in vacuum, contributes to the formation of a martensitic structure, an increase in the dispersion of the $\alpha$-phase plates to fractions of 1 micron, which is accompanied by an increase in microhardness to the level of 400HV. For Ti-Al-V-Mo-Zr system alloys, an increase in the cooling rate promotes the formation of a thinner lamellar structure.

4. Conclusions
The studies have shown that the technology of wire vacuum-arc surfacing prospectively can be effectively used to form defect-free heat-resistant titanium alloys workpieces.
It was found that with an increase in current and wire feed speed, an increase in the height and width of the deposited beads occurred.

Undercuts along the fusion line are observed by upscaling of arc current to 150A and by reducing the wire feed speed. A decrease in the arc current to 120A leads to the disappearance of undercuts, even at a low wire feed speed, and to a decrease in the heat-affected zone size.

A decrease in the arc current, and, consequently, a decrease in the volume of the deposited metal increases the cooling rate, which leads to an increase in the fraction of the martensite phase and an increase in the microhardness above 400 HV.

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