Application of plasma surfacing for additive formation of titanium alloy billets

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This paper presents the findings of an investigation on the main formation regularities of structure and properties of VT20 (BT20) superalloy of Ti – Al – V – Mo – Zr system in hybrid technology of additive manufacturing with the use of plasma surfacing with layer-by-layer strain hardening. When studying the effect of forging on the structure and properties of surfacing material, three processing schemes were implemented: surfacing with forging of a next to last layer; surfacing with forging of the last layer; surfacing with forging of each layer.

Investigated is the morphology of the built-up layers' structure, which is associated with various cooling rates at the stages of crystallization and transformations in the solid state: at high cooling rate, a basket weave structure is forming, and a martensite-like lamellar structure arises on slow cooling. Different dispersities of the plates of α -colonies were fixed — from 200 to 500 μm , the size of individual needles varies from fractions of a micron to 100 μm .

It is established that the layer-by-layer deformation impact, which contributes to the titanium alloy structure grinding and a rise in dispersion of the α -phase plates, is accompanied by an increase in microhardness to the level of 6000 HV. The formation of a finer structure during surfacing with a layer-by-layer deformation effect is obviously bound up with the martensite phase lightened growth on a pre-crushed metal substrate with an increased dislocation density.

It is established that the strength properties of the obtained VT20 alloy surfacings exceed the strength level of materials made by traditional forming technologies, and there is no decrease in the plasticity characteristics.

Key words: titanium alloys, additive technologies, plasma surfacing, layer-by-layer deformation impact, structure, properties.

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Introduction

At present time, the task of modernizing the existing and introducing new technologies, in particular, hybrid additive technologies, aimed at the production of large-sized figurine-shaped titanium blanks, is acute in the aircraft industry, propulsion engineering and shipbuilding industry. It is the introduction and application of hybrid additive technologies that allows one to fully implement the basic principles of creating the new-generation materials, which is a strategic priority for the development of materials and technologies until 2030, that are based on the results of fundamental and fundamentally-oriented investigations obtained by leading scientific and technological organizations. Abroad, such giants as GE, Boeing and MTU Aero take first place in the market of the products manufactured by additive technology.

In modern aircraft engine building, the figurine-shaped components which cannot be made by traditional “subtractive” technologies (machining, casting etc.) are designed for promising parts and constructions made of hard-to-machine materials. In the aerospace industry, reducing the product weight makes it possible to save fuel and lower harmful emissions. Therefore, the design of the parts with a cut weight while keeping functionality is one of the main tasks in this industry. Organization of high-tech production of metal parts by means of additive technology opens up new opportunities for obtaining articles with optimized geometry.

Lessening the number of technological stages, labor intensity and production time of the part obtained by the

additive method leads to a proportional reduction in material and time consumption, which significantly increases manufacturability of the product and efficiency of equipment.

The use of additive arc processes, which make it possible to synthesize large-sized components with minimum allowance for machining and mechanical properties at the metal level of traditional technologies, permits to obtain significant metal saving and reduce many-fold the production tooling spendings [1–7]. This fully applies to making products of such expensive materials as titanium alloys [8–9].

One of the most effective technologies of additive manufacturing — plasma surfacing — has been employed in this work. The use of plasma surfacing provides a number of advantages, both from a technological and economic point of view. These include high productivity in the manufacturing of products by layer-by-layer synthesis, wide-range regulation of heat transfer to the main and surfaced material, and, as a result, control of the melting-through depth and width, structure, composition and properties of the formed material.

However, a significant disadvantage of titanium alloys in welding and surfacing technologies is some structural features, in particular, unfavorable dendritic structure, anisotropy, banding due to transcrystalline adjustment of dendritic clusters, and as a result, a decrease in mechanical properties (the breaking point σ^{20} is below 850 MPa), notably, loss of plasticity [8–12].

The solution to these problems can be a layer-by-layer deformation effect that can increase the deposited material density, crush the structure with the resulting increase in mechanical properties. The improvement of microstructure and strength characteristics of the material occurs during the process of deformation effect on each layer of the surfaced solid material (3–5 mm thick) by rolling, forging or ultrasonic impact treatment. The subgrain microstructure formed in this way does not disappear during the fusing of subsequent layers, i.e. prove to be thermally stable. The positive effect of the rolling deformation treatment on the strength of products during layer-by-layer synthesis is described in [13]. In [14], the authors has showed that the use of layer-by-layer forging not only reduces the process residual stresses and changes their sign on the surface of the product from tensile to compressive, but also leads to a decrease in grain size, an increase in strength characteristics to the level of the base metal, a decrease in porosity and anisotropy.

The authors of the work [15] has found that the use of ultrasonic impact treatment of titanium alloy welds provides the formation of surface compressive residual stresses in them and increases the fatigue characteristics of the weld material by more than 6 times.

The aim of this work was to investigate the main formation regularities of the structure and properties of VT20 titanium superalloy of Ti – Al – V – Mo – Zr system in the hybrid technology of additive manufacturing with the use of plasma surfacing. Special attention is paid to the study of an influence of shock deformation by forging on layer-by-layer growing of the article. The task was set to ensure the resulting metal density not less than 99.5% and mechanical properties not less than 90% of the values of the source material's characteristics.

The surfacing material — VT20 alloy, which is based on the Ti – Al – V triple system typical for most high-strength titanium alloys, belongs to near α -alloys. In accordance

with the principles of heat-resistant alloying of titanium alloys, the multicomponent alloy is doped with α -stabilizers (Al), β -stabilizers (V, Mo, Fe, Zr) and contains neutral reinforcing agents (C, N), which provides an effective combination of dispersion and solid-solution hardening mechanisms. The composition of the heat-resistant matrix α -solution is selected so that the diffusion mobility of the atoms is as minimal as possible and the solution-precipitation mechanisms leading to the enlargement of the dispersed phases proceed at the lowest speed. Aluminum at the introduction level of more than 5% wt. not only increases the heat resistance of near α -alloys, but it also significantly increases the solubility of isomorphic β -stabilizers (iron, vanadium, molybdenum) in α -phase, creating additional opportunities for solid-solution hardening of the alloy with these elements. Vanadium alloying additionally provides a low susceptibility to hydrogen embrittlement. Of the non-metals, the most important for increasing the heat resistance of VT20 alloy is silicon, which acts by the mechanism of blocking dislocations at high temperatures and prevents their sliding owing to the large parameter of a dimensional mismatch of Si and Ti atoms [16], as well as elements that form the interstitial solid solutions — carbon, nitrogen.

Technologies, research procedures and materials

Plasma surfacing was performed on a unit developed at the PNRPU Plasma Technology Research Center; the process diagram is shown in **Fig. 1**. Surfacing modes are as follows: current — 200 A, filler wire diameter — 1.2 mm, surfacing speed — 12 m/h, wire feed speed — 3 m/min, protective gas (argon) flow — 8 l/min, plasma — forming gas (argon) flow — 3 l/min, gas (argon) flow to protect the weld tail part — 15 l/min.

A Sumake ST-M3009/H manual air hammer is used for layer-by-layer strain hardening of samples. Due to its small weight and dimensions, strain hardening can be performed with minimal delay after surfacing. The chemical composition of the VT20-2sv (BT20-2CB) surfacing wire is given in **Table 1**.

To conduct studies of mechanical characteristics of the surfaced metal, macro- and microstructural analysis, there were deposited the blanks in the form of a flat wall, from which the samples were cut out for testing. The type of the deposited wall and the shape of a single VT20 alloy roller during plasma surfacing with strain hardening is shown in **Fig. 2**.

Structural investigations of the surfaced material and fusion zones between the layers were carried out using light microscopy (Neophot 32). Quantitative metallographic analysis was performed on a Videotest-metal automated software and hardware complex for image analysis and structural modeling based on an Altami-587 metallographic microscope. Microhardness tests were implemented on a PMT-3 (ПМТ-3) unit at

Fig. 1. Diagram of the plasma surfacing process

Table 1

Chemical composition of the VT20 surfacing wire

Alloy grade	Content of elements, % wt.										
VT20-2sv	Al	V	Mo	Zr	Si	Fe	C	N	O	H	Ti
	4.1	1.1	1.2	1.6	up to 0.1	0.11	0.03	0.01	0.13	0.001	base

a load of 200 g with a 0.15-mm step. Tests of strength properties were performed in accordance with GOST 9454–78, test complex INSTRON 5982. The chemical composition was analyzed by spectral analysis according to GOST 23902–79. The porosity of the deposited layers was analyzed using the SIAMS PhotoLab quantitative metallographic analysis complex.

Research on the macrostructure of the VT20 alloy surfaced layers

For a detailed study of the forging influence on the surfacing material structure and properties, three processing schemes were carried out: surfacing with forging of a next to last layer; surfacing with forging of the last layer; surfacing with forging of each layer.

Fig. 3 shows the fragments of the surfaced metal macrostructure when surfacing with forging of a next to last layer and surfacing with forging of the last layer.

The surfaced metal macrostructure is lamellar, of dendritic structure, with the overlap of adjacent paths. The dendrites are oriented in the direction opposite to the heat sink. Banding of the structure is observed — growing of dendritic clusters with different etchability of the metal through several surfaced layers, the so-called transcrystallization. A small change in the microhardness along the surfacing height was revealed (measurements were carried out starting from the top layer down). Porosity in the surfaced layers is absent for all processing modes.

As can be seen from comparison of the results in Fig. 3, the first two variants did not result in significant structure change. Besides, the microhardness throughout the height of the surfaced layer practically does not change — it remains at the level of 4000 ± 200 H/mm².

Analysis of the macrostructure of the surfaced layers with forging of each layer (Fig. 4) showed that the size of dendritic colonies and transcrystallization areas has been significantly decreased — their maximum length is no more than 2 mm in comparison with Fig. 3, where the size of these areas reached 8 mm. The microhardness level of the alloy when surfacing with layer-by-layer forging is significantly higher — by 10–15%, the maximum value is up to 6000 H/mm².

Studies of microstructure of the VT20 alloy surfaced layers

The deposited wall microstructure analysis has revealed the presence of areas with different mor-

phology, size, and nature of the phase relative position (Fig. 5).

The typical structure of a Ti – Al – Zr – Mo – V system titanium alloy in the heat-treated state is observed:

Fig. 2. An appearance of the surfaced wall (a) and the shape of a single roller (b) of VT20 alloy during plasma surfacing with strain hardening

Fig. 3. Macrostructure and distribution of microhardness HV0.2 throughout the height H of the surfaced wall layers: a — surfacing with forging of a next to last layer; b — surfacing with forging of the last layer

Fig. 4. Macrostructure (a), line of measurements of microhardness HV0.2 (b) and a diagram of its distribution (c) throughout the height H of the surfaces wall layers on surfacing with forging of each layer

Fig. 5. Microstructure of various sections of the surfaced layers

a small amount of the initial β -grain (in fact, it is guessed only by thin strata along the grain boundaries), colonies of α -plates of different sizes with the α -phase intragrain

plates of different thickness. According to [16], the diversity of structures is caused by different crystallization conditions as a result of different temperature cycles of surfacing and hot plastic deformation. Sections of coarse grain (more than $500\text{ }\mu\text{m}$) with coarse intragrain plates (sections 4–6 in Fig. 5), smaller micrograin and thin-plate intragrain structure (sections 1 and 3 in Fig. 5), as well as sections with a moderate value of the initial β -grain, no more than $200\text{ }\mu\text{m}$, and an intragrain basket weave structure (section 2 in Fig. 5) were stated.

The surfaced layers are also characterized by different dispersities of the plates of α -colonies, and the size of individual needles — from fractions of a micron to $100\text{ }\mu\text{m}$. Such difference in the morphology of the structure is explained by different cooling rates at the crystallization stage and at the stage of transformations in the solid state. At a high cooling rate, a basket weave structure with a microhardness of 6000 HV is formed (section 2 in Fig. 5.). On slow cooling, a lamellar structure represented by colonies of almost parallel α -plates (sections 4–6 in Fig. 5.) with a microhardness of $4000\text{--}3500\text{ HV}$ is generated.

The formation of a finer structure on surfacing with a layer-by-layer deformation impact is obviously associated with the facilitated growth of the martensite phase on a pre-crushed metal substrate with an increased dislocation density. This phenomenon is similar to the

formation of a more dispersed structure on pre-deformed workpieces during annealing.

Fig. 6 represents a thermal cycle of the VT20 alloy plasma surfacing.

The temperature T (K) dependence on the time τ is obtained using the Green's function method for an infinite plate with zero Newmann's boundary conditions and a normal-circular source:

$$T = \frac{0.85 \cdot q}{4c \cdot \gamma \cdot (\sqrt{\pi \cdot a})^3} \cdot \int_0^t \frac{1}{(\sqrt{\tau})^3} \exp \left[-\frac{(x + V \cdot \tau)^2 + (y)^2}{4 \cdot \tau \cdot a} \right] \times \\ \times \sum_{N=-\infty}^{\infty} \exp \left[\frac{-(z + 2 + N \cdot L)^2}{4 \cdot \tau \cdot a} \right] d\tau,$$

where q is the arc power; a is a thermal conductivity coefficient; c , γ are heat capacity and density of the alloy; V is the surfacing rate; L is the layer thickness; t_0 depends on the arc concentration coefficient; x , y , z , and N are the coordinates. Obviously, with this mode of the surfaced wall formation, we are the nearest to the optimal mode of traditional heat treatment of heat-temperature titanium near α -alloys (annealing at 900–950 °C, holding time of 1 hour, air cooling), which provides the highest values of long-term strength and satisfactory thermal stability [16]. An even more obvious analogue of the thermal impact on multilayer surfacing is the double annealing of deformable titanium blanks, the second stage of which consists in heating at 550–680 °C. As shown by thermal models of surfacing [17], this temperature is a characteristic feature of the preceding surfaced layer when the subsequent layer is superimposed. The structure of the alloy is not significantly affected by the cooling rate after heating in $\alpha + \beta$ zone of the alloy and changes only after heating in a β -zone. As the cooling rate increases, a thinner lamellar structure is formed. It is traditionally considered [16, 18] that alloys with a basket weave structure provide a higher crack strength in comparison with the structures represented by α -colonies, and even more so by globular structures, but at the same time the plasticity characteristics are somewhat reduced.

Thus, it is stated that the layer-by-layer deformation impact contributes to the grinding of the titanium alloy structure by approximately 2–3 points and increases the dispersity of the α -phase plates to fractions of a micron; this is accompanied by an increase in microhardness to the level of 6000 HV.

Fig. 6. Thermal cycle of a VT20 alloy surfacing:

— the first layer; --- the second and subsequent layers; representative temperatures $T_{liq} = 1935$ K; the solidus temperature $T_{sol} = 1723$ K; the polymorphic transformation temperature $T_{pt} = 1293$ K

It is shown below that there is no reduction in the plasticity characteristics for the grown VT20 material.

Research on mechanical properties of VT20 alloy under plasma additive surfacing with layer-by-layer strain hardening

Table 2 contains test results of mechanical properties of VT20 alloy obtained by plasma additive surfacing with layer-by-layer strain hardening. For comparison, the mechanical properties of materials produced by traditional forming technologies are also given there.

The analysis of the results shows that the surfaced material's strength characteristics reach the level of the bar properties — 890 MPa, and exceed it in respect of the yield strength $\sigma_{0.2}$ (825 MPa versus 800 MPa). The plasticity of the surfaced lamellar VT20 alloy is significantly higher than that of the bars — relative narrowing reaches 40%, which is a very high indicator for titanium alloys (compared to the data of the work [19]). Moreover, the impact elasticity of a synthesized material also exceeds the viscosity of a rod material by 1.8 times.

Conclusions

1. The performed investigations have shown that the hybrid technology of multilayer plasma surfacing with layer-by-layer strain hardening allows to use the high-tech titanium superalloys to produce the articles of a given geometric shape.

Table 2
Mechanical properties of VT20 alloy obtained by various technologies

Sample	Property				
	σ , MPa	$\sigma_{0.2}$, MPa	δ , %	ψ , %	KCU, kgf-m/cm ²
VT-20 (plasma additive surfacing with layer-by-layer strain hardening of each layer; without heat treatment)	895	825	11.6	40.8	5.6
VT20 bar, annealing, GOST 26492–85	885	—	8..10	20	3.4
VT6 annealing, GOST 26492–85	855...889	765...800	No less than 5..6	15–20	2.5

2. It is shown that the morphology difference of the surfaced layers' structure results from different cooling rates at the stages of crystallization and transformations in the solid state: at high cooling rates, a basket weave structure is formed; and a martensite-like lamellar structure represented by colonies of almost parallel α -plates arises on slow cooling. Different dispersities of the plates of α -colonies were determined — from 200 to 500 μm , the size of individual needles varies from fractions of a micron to 100 μm .

3. It was determined that the layer-by-layer deformation effect contributes to the grinding of the titanium alloy structure and increases the dispersity of the α -phase plates, which is accompanied by an increase in microhardness to the level of 6000 HV.

4. It was found that the strength characteristics of the VT20 alloy obtained by layer-by-layer plasma surfacing exceed the strength level of materials produced by traditional forming technologies, and there is no decrease in the plasticity parameters.

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