Surface modification of additive manufactured metal products by an intense electron beam

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Abstract. On the example of VT6 titanium alloy it is shown that successive surface modification of additive manufactured metal specimens in vacuum at an argon pressure of 3.5·10⁻² by ten pulses with 200 µs, 45 J/cm² and then by three pulses with 50 µm, 20 J/cm² provides a considerable decrease in their porosity and surface roughness (20 times for Rₚ) while their surface microhardness, friction coefficient, and wear level remain almost unchanged. After electron beam irradiation, the ultimate tensile strength of the material increases 1.33 times, and its tensile strain 1.18 times. For specimens obtained by conventional metallurgy and irradiated in the same modes, no such effects are observed.

1. Introduction

Today, 3D printing is much used in different technologies such as those of aircrafts, space crafts, submarines, tools, prostheses, implants, jewelry, etc. [1–4]. Additive manufacturing uses computer models to create 3D objects by joining materials layer by layer rather than by removing some, for which it differs from conventional mechanical technologies. Additive processes are classified by material (liquid, loose, polymer, metal powder, metal wire), process assistance (laser, electron beam), binding method (heat, UV or visible radiation, binding agent), and layer formation (selective laser or electron beam sintering, jet printing). For selective sintering, powder material is uniformly distributed on a platform and selectively sintered with a laser or electron beam according to a current model cross-section. For jet printing, material is deposited directly to the point of energy delivery [5].

Now, metal objects are most often grown using 3D printers based on selective laser or electron beam sintering. The formation of an object occurs in a thin (50–100 µm) layer of metal powder where individual particles are sintered under the action of heat. The problem common to all additive technologies concerns porosity in a synthesized material. Some studies show that porosity varies with material and fusion mode [6]. For example, for aluminum and titanium alloys, it can reach 4–5 % and 2 %, respectively, and for steels, it is less than 0.2 %. Porosity can be minimized by repeated fusion of layers [7, 8], i.e., each layer is sintered twice with a laser, which decreases this parameter an order of magnitude but almost doubles the growth time of an object. Another problem in additive technologies concerns anisotropy (structural, mechanical) and high internal stress, which is inevitable in the layer-by-layer synthesis of an object. At the interface of an object and powder, a highly rough porous layer is often formed due to insufficiently fused powder particles.

Here we report on the use of a submillisecond pulsed electron beam for decreasing the surface roughness and porosity of VT6 titanium alloy specimens manufactured by selective electron beam sintering of powder particles of size 40–100 µm.
2. Material and research techniques
The test specimens were VT6 titanium plates of dimensions 15×15×2 mm obtained from metal powder particles of size 40–100 µm by selective electron beam sintering in vacuum (Arcam A2X, Sweden). For comparison, we used VT6 specimens cut from a bar of diameter 15 mm parallel to its longitudinal axis; their preliminary thermomechanical treatment conformed to GOST 22178-76. Part of the specimens was irradiated with an intense pulsed electron beam on the SOLO setup [9] in two successive modes: ten pulses with an electron energy of 15 keV, energy density of 45 J/cm², duration of 200 µs, and repetition frequency of 0.3 s⁻¹ (mode I) and three pulses at 15 keV, 20 J/cm², 50 µs, and 0.3 s⁻¹ (mode II). The operating pressure was 3.5·10⁻² (Ar). Mode I greatly decreases the surface roughness and porosity of e-beam sintered VT6 specimens [10]. This mode was used for pre-polishing, and mode II for further finishing.

The surface roughness of the specimens was measured on an MNP-1 optical profilometer (sampling length 0.8 mm, no less than ten measurements per specimen), and their surface microhardness was measured on an PMT-3M device (no less than ten points in different regions at a load of 0.5 N).

The specimens were tested for tension on an Instron 3369 machine at a rate of 0.2 mm/min and temperature of 20 °C. Their gage section parallel-sided lengthwise and right-angled at the ends had an initial thickness, width, and length of 2.0 mm, 2.0 mm, and 10 mm, respectively.

The specimens were also tested for dry friction on a TRIBotechnic ball-on-disk tribometer with a hard WC–Co ball of diameter 6 mm. The conditions were the following: room temperature, relative humidity 50 %, normal indenter load 3 N, sliding velocity 2.5 cm/s, track diameter 4 mm, sliding distance 15 m. The wear volume was determined after profilometry of a formed track.

The surface structure was examined on a Philips SEM-515 scanning electron microscope (Uₘₐₓ = 30 kV).

3. Research results and discussion
Figure 1 shows the surface structure of additive manufactured VT6 specimens before and after pulsed electron beam treatment. Their initial surface is rough and porous and reveals stuck powder particles. After pulsed electron beam irradiation, both in mode I and II, their surface layer assumes a homogenous polycrystalline structure, its porosity decreases, and powder particles are indistinguishable.

![Figure 1. Surface structure of additive manufactured VT6 specimens before irradiation (a), after irradiation in mode I (b), and after successive irradiation in mode I and II (c).](image_url)

The surface roughness of the additive manufactured VT6 specimens before and after pulsed electron beam irradiation is presented in Table 1. As can be seen, Rₕ after irradiation decreases ~20 times and Rₜ decreases ~19 times, and an additional decrease in Rₜ and Rₚ is provided by irradiation in mode II.

The surface microhardness of the specimens is presented in Table 2. The measurements show that this parameter after irradiation remains unchanged (measurement error ~10%). The friction coefficient and wear parameters before and after irradiation are close in value (Table 2). After irradiation in mode II, the tribological properties reach the initial level.
Table 1. Surface roughness of additive manufactured VT6 titanium specimens

| State     | Roughness Ra, µm | Roughness Rz, µm |
|-----------|------------------|------------------|
| Initial   | 20.2±1.5         | 93.8±10          |
| Mode I    | 1.3±0.5          | 6.2±1.5          |
| Mode I+II | 1±0.5            | 5±1.5            |

Table 2. Surface microhardness and wear of additive manufactured VT6 titanium specimens

| State     | Hardness, HV50 | Fraction coefficient | Wear groove depth, µm | Specific wear rate, 10^-4 mm³/N·m |
|-----------|----------------|----------------------|-----------------------|-----------------------------------|
| Initial   | 306            | 0.36                 | 8.5                   | 4.6                               |
| Mode I    | 324            | 0.41                 | 9.2                   | 5.9                               |
| Mode I+II | 303            | 0.32                 | 8.4                   | 5.2                               |

Analyzing the data of tensile tests in Table 3 and Fig. 2, one can see that the highest mechanical properties are found for the additive manufactured specimens after pulsed electron beam irradiation: the tensile strength increases 1.33 times, and the tensile strain 1.18 times. The ductility of the specimens obtained by conventional metallurgy decreases after irradiation in the same modes. Our study shows that the difference in the mechanical properties of the materials is due to differences in their defect structure. After intense pulsed electron beam irradiation, the additive manufactured material reveals a polycrystalline structure with a grain size of 15–60 µm and a cellular structure with a cell size of 0.5–1.2 µm in the grain volume. The material obtained by conventional metallurgy assumes a polycrystalline structure with a grain size of 50–800 µm and a rough lamellar structure in the grain volume.

Figure 2. Strain hardening curves for VT6 titanium alloy under tension: 1 – additive manufacturing; 2 – additive manufacturing and irradiation; 3 – conventional metallurgy; 4 – conventional metallurgy and irradiation.
Table 3. Tensile data for additive manufactured (AM) and casted (C) VT6 titanium specimens

| State                | Ultimate tensile strength, MPa | Tensile strain, % | Displacement at ultimate tensile strength, mm |
|----------------------|-------------------------------|------------------|---------------------------------------------|
| Initial (AM)         | 783.6                         | 16.1             | 1.59                                        |
| Mode I+II (AM)       | 1047.2                        | 19               | 1.67                                        |
| Initial (C)          | 774.5                         | 15.9             | 1.39                                        |
| Mode I+II (C)        | 776.8                         | 14.2             | 1.12                                        |

4. Conclusion

Thus, on the example of VT6 titanium alloy, it is shown that pulsed electron beam irradiation provides the formation of a homogeneous polycrystalline structure and greatly decreases the porosity and surface roughness in electron beam sintered materials: ~20 times for $R_a$. The strength and tribological properties remain the same as in the initial material. The highest tensile strength and ductility is found in the additive manufactured specimens exposed to pulsed electron beam irradiation: these parameters increase 1.33 and 1.18 times, respectively. The ductility of the material obtained by conventional metallurgy decreases after irradiation in the same modes. The proposed method of successive pulsed irradiation at an energy density of $>30$ J/cm$^2$ and $\leq 20$ J/cm$^2$ can modify the mechanical properties and greatly decrease the surface roughness of additive manufactured materials with $R_a > 3 \mu m$.

Acknowledgments

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