Structure and mechanical properties of stainless-steel specimens, made by additive method, after pulsed electron beam treatment

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Abstract. The article presents a method for finishing the surface of metal products made by sequential electron-beam surfacing, which consists in modifying the surface with an intense low-energy electron beam of submillisecond duration. On the example of 308LSi stainless steel, the results of such processing are demonstrated, the optimal modes of exposure are determined. It is shown that as a result of pulsed electron-beam processing, a homogeneous polycrystalline structure without cracks is formed on the surface with unchanged, relative to the initial material, elemental composition, strength (microhardness) and tribological (wear rate) properties. In this case, the surface roughness is reduced to 2.1 times in the longitudinal direction relative to the surfacing plane, to 5.2 times in the transverse direction. Tensile tests of specimens showed anisotropy of mechanical properties depending on the direction of tension relative to the surfacing plane, which decreases after surface pulse electron-beam processing.

1. Introduction

Today it is difficult to find an area of production where 3D-printers are not used: they are used to manufacture parts of aircraft, spacecraft, submarines, instruments, prostheses and implants, jewelry, etc. [1-4]. The essence of additive manufacturing is to connect materials layer by layer to create objects from 3D-model data. In this way, they differ from traditional production technologies, which imply mechanical processing, i.e. removal of the matter from the workpiece. Additive technologies are classified [2]: by the materials used (liquid, bulk, polymer, metal-powder, metal-wire); by the method of fixing the layer (thermal effect, irradiation with ultraviolet or visible light, binder composition); by the method of layer formation (selective laser or electron-beam sintering (fusion) of powder, laser or electron-beam surfacing of the wire material, inkjet printing). Selective sintering (fusion) means that, first, a powder material is poured onto the platform and evenly distributed to create a layer of a given thickness (bed deposition), then it is selectively sintered (fused) with a laser or an electron beam according to the current cross-section of a previously prepared model [1, 2]. The formation of a layer by the method of surfacing (direct deposition) consists in deposition of the material at the point of energy supply by the simultaneous melting of the supplied metal wire and the surface layer of the
substrate [1, 2]. Inkjet printing has a similar principle of layer formation, where the material is selectively deposited in melted form and hardens over time [2].

3D-printers based on selective laser or electron-beam sintering (fusion) of metal powder, or surfacing of wire material fed directly into the melting point are currently used to grow metal products. A common problem typical for the presented types of additive technologies is the problem of surface finishing of products synthesized from a metal material. For powder technologies, it is due to the adhesion of separated powder particles to the surface of the product at the sintering (fusion) boundary during layer-by-layer growth. In this case, a coarse porous structure is usually formed, the roughness of which can reach several tens-hundreds of micrometers [5]. In the case of wire technologies, a coarse wavy structure with a roughness of up to several hundred micrometers is often formed on the lateral surface of products and characterizes each separate layer of the surfacing. Earlier [6], it has been shown from VT6 titanium alloy specimens that, pulsed electron beam polishing can be used along with traditional surface finishing techniques of metal articles (mechanical processing, chemical, electrochemical etching) and allows multiple (up to 20 times) to reduce the roughness and porosity of the surface layer without deteriorating its strength and tribological properties.

In this work, an intense pulsed electron beam of submillisecond duration was used to reduce the surface roughness of 308LSi stainless steel specimens manufactured by layer-by-layer electron-beam surfacing of the material formed during melting a metal wire.

2. Materials and research methods

Stainless steel 308LSi (0.01% C, 19.9% Cr, 0.1% Cu, 1.8% Mn, 0.15% Mo, 10.5% Ni, 0.9% Si, the rest Fe) was chosen as a material for research, the wire from which is widely used for welding (surfacing) stainless steels (OK Autrod 308LSi, “ESAB”, thickness of 1 mm). The synthesis of the specimens was carried out in a vacuum chamber using an electron-beam gun with a thermionic cathode on a setup developed by TETA LLC (Tomsk, Loskutovo village) [7]. Initially, several linear formations up to 10 cm long, up to 4 cm high and up to 0.6 cm thick were grown in parallel on a massive steel billet. Then, using electric spark cutting, 12×12×4 mm specimens with sections of the lateral surface were cut out of the resulting formations. Mechanical tensile tests were carried out on flat dumbbell-shaped specimens. To determine the anisotropy of mechanical properties, the specimens were cut so that tension was carried out in the longitudinal and transverse directions relative to the surfacing plane for 3 specimens per treatment mode.

Part of the manufactured specimens were irradiated with an intense pulsed electron beam at the SOLO setup [8, 9]. The specimens were irradiated under sequential exposure in two modes: an energy of accelerated electrons is 15 keV, an energy density in the pulse is 40 J/cm², a pulse duration is 150 μs, a number of pulses per surface area is 10, a pulse repetition rate is 0.3 s⁻¹ (mode No. 1) and, accordingly, 15 keV, (12-20) J/cm², 50 μs, 3 pls., 0.3 s⁻¹ (mode No. 2). The processing was carried out in a vacuum chamber in an argon atmosphere at a pressure of 3.5×10⁻² Pa. These irradiation modes were selected on the basis of earlier studies for specimens of VT6 titanium alloy [6], prepared by layer-by-layer selective electron-beam fusion in vacuum. Studies have shown that the regime with a pulse duration of (150-200) μs and an energy density in the pulse of (30-45) J/cm² can significantly reduce the roughness and porosity of the surface layer of the specimens, and the regime with a pulse duration of 50 μs and an energy density in the pulse of (10-20) J/cm² to restore strength and tribological properties. Thus, mode No. 1 was used for preliminary “rough” polishing, and mode No. 2 for subsequent finishing.

To determine the optimal modes of finishing the surface of 308LSi stainless steel, a complex of studies of the structure and properties of the treated specimens was carried out in comparison with the initial material.

To study the surface structure of the specimens, Philips SEM-515 scanning electron microscope was used (Umax = 30 kV). Elemental analysis of the specimen surface was carried out by microelectron diffraction using an EDAX ECON IV microanalyzer.
The study of the microhardness of the surface of the specimens was carried out on PMT-3M device. The measurements were carried out at no less than ten points on different parts of the surface at a load of 0.5 N.

To determine the tribological properties of the surface, part of the specimen before finishing with a pulsed electron beam was ground on a diamond wheel to bring the initial surface to the same roughness level. Carrying out tribological tests without preliminary grinding could lead to an incorrect comparison of the results due to the large difference in the surface topology of the specimens. Tribological tests were carried out with dry friction according to the disk-ball scheme on TRIBOtechnic device. The indenter (counterbody) was a 6 mm diameter WC-Co hard alloy. The tests were carried out at room temperature and 50% relative humidity under the following conditions: normal load on the indenter is 3 N, sliding speed is 2.5 cm/s, track diameter is 4 mm, distance traveled by the ball is 15 m. The volume of material wear was determined after profilometry of the formed track.

The roughness of the surface of the polished specimens before and after irradiation was investigated using MNP-1 optical profilometer (base length is 0.8 mm, at least ten measurements per specimen). The roughness of specimens with the initial surface topology was investigated using TRIBOtester contact profilometer, while measurements were carried out both longitudinal to the surfacing plane and transverse for each specimen (base length is 4 mm, at least five measurements per direction).

Mechanical tensile tests of the material were carried out on an Instron device (model 3369). The initial thickness, width and length of the working part of the specimens are 1.8 mm, 1.8 mm and 10 mm, respectively; test speed is 0.2 mm/min; ambient temperature is 24°C. The specimens were irradiated with a pulsed electron beam from both flat sides.

3. Results and discussion

Figure 1 shows photographs of the surface structure of 308LSi stainless steel specimens manufactured by electron beam surfacing. Scanning electron microscopy showed that pulsed electron treatment in all the presented irradiation modes leads to the formation of a homogeneous polycrystalline structure without cracks, in contrast to the original specimen.

![Figure 1. Surface structure of 308LSi stainless steel specimens made by electron-beam surfacing, before (a) and after (b) processing by a pulsed electron beam (mode No. 1 + mode No. 2 (20 J/cm²)).](image)

The elemental composition of the surface of the specimens after irradiation approached the tabular values for 308LSi stainless steel (table 1). All basic elements are present on the surface, the content of which is within acceptable limits. The quantitative deviation of some elements from the tabulated values is due to the high errors of the microelectron diffraction method, as well as the fact that oxygen
was not taken into account in these studies, which introduces an even greater error in the relative distribution of elements.

Table 1. Elemental composition of the surface of 308LSi stainless steel specimens before and after pulsed electron-beam processing.

| Element | Initial (at.%) | After EB processing (at.%) | Table values for 308LSi (at.%) |
|---------|----------------|----------------------------|-------------------------------|
| Si      | 2.1            | 1.89                       | 0.9                           |
| Cr      | 12.82          | 21.03                      | 19.9                          |
| Mn      | 0.4            | 0.98                       | 1.8                           |
| Fe      | 70.28          | 62.67                      | 66.7                          |
| Ni      | 9.9            | 7.05                       | 10.5                          |
| Cu      | 0              | 0.81                       | 0.1                           |
| Mo      | 4.5            | 5.58                       | 0.15                          |

Investigations of the microhardness of the surface layer of the specimens after pulsed electron-beam treatment did not reveal any changes in all irradiation modes with respect to the initial material (Table 2). At the same time, studies of the tribological properties of the surface of the specimens showed that the wear rate depends on the irradiation mode and for most modes exceeds the result of the initial specimen. However, for mode No. 1 + No. 2 (20 J/cm²), the wear parameter corresponds (taking into account the measurement error) to the initial material. The friction coefficient of the irradiated surface decreases, depending on the irradiation mode, from 1.08 to 1.34 times as compared to the untreated surface.

Table 2. Microhardness and surface tribology of 308LSi stainless steel specimens before and after pulsed electron-beam processing.

| Processing mode | Microhardness (HV₅₀) | Friction coefficient | Wear rate (10⁻⁴ mm³/N·m) |
|-----------------|-----------------------|----------------------|--------------------------|
| Initial         | 191                   | 0.82                 | 6.1                      |
| Mode No. 1      | 171                   | 0.66                 | 7.7                      |
| Mode No. 1 + No. 2 (12 J/cm²) | 183       | 0.66                 | 8.5                      |
| Mode No. 1 + No. 2 (15 J/cm²) | 187       | 0.76                 | 8.7                      |
| Mode No. 1 + No. 2 (18 J/cm²) | 180       | 0.61                 | 6.9                      |
| Mode No. 1 + No. 2 (20 J/cm²) | 179       | 0.71                 | 6.4                      |

To determine the irradiation mode that creates a surface with a minimum roughness, preliminary studies were carried out on specimens, the surface of which was mechanically ground before irradiation to create the same initial roughness. The research results are presented in Table 3, from which it can be seen that the minimum roughness (Rₐ = 1.41 μm) was shown by the irradiation mode No. 1 + No. 2 (20 J/cm²). In this mode, further electron-beam processing of specimens, the surface of which corresponded to the lateral surface of the products obtained by the method of electron-beam surfacing was carried out.

Table 4 shows the results of measuring the longitudinal and transverse roughness, obtained by averaging the results of three specimens, indicating the maximum deviation from the average value, before and after irradiation. It is shown that the surface treatment of 308LSi stainless steel specimens made by electron beam surfacing with a pulsed electron beam allows reducing the surface layer roughness up to 2.1 times (Rₐ) in the longitudinal direction and up to 5.2 times (Rₐ) in the transverse direction.
Table 3. Roughness of the surface of polished specimens of 308LSi stainless steel before and after pulsed electron-beam processing.

| Processing mode                     | $R_a$ (µm) | $R_z$ (µm) |
|-------------------------------------|------------|------------|
| Initial                             | 2.73       | 15.21      |
| Mode No. 1                          | 1.44       | 6.31       |
| Mode No. 1 + No. 2 (12 J/cm$^2$)   | 1.56       | 7.26       |
| Mode No. 1 + No. 2 (15 J/cm$^2$)   | 1.86       | 7.92       |
| Mode No. 1 + No. 2 (18 J/cm$^2$)   | 1.73       | 7.33       |
| Mode No. 1 + No. 2 (20 J/cm$^2$)   | 1.41       | 5.83       |

Table 4. Surface roughness of 308LSi stainless steel specimens with initial surface topology before and after pulsed electron-beam processing.

| Processing mode                     | Longitudinal to the surfacing direction | Transverse to the surfacing direction |
|-------------------------------------|----------------------------------------|---------------------------------------|
|                                     | $R_a$ (µm) | $R_z$ (µm) | $R_a$ (µm) | $R_z$ (µm) |
|-------------------------------------|------------|------------|------------|------------|
| Initial                             | 3.01 ± 0.3 | 17.67 ± 2.5 | 7.09 ± 3.9 | 39.06 ± 29 |
| Mode No. 1 + No. 2 (20 J/cm$^2$)   | 2.07 ± 0.5 | 8.23 ± 1.6 | 3.6 ± 1.5  | 13.55 ± 4.7 |

Tensile tests of the specimens showed an increase in plasticity after pulsed electron-beam treatment (mode No. 1 + No. 2 (20 J/cm$^2$)) by 10.6% in the longitudinal direction with an initial tensile strain of 72%. In the transverse direction, tensile strain reached 88% and did not change after processing. The maximum tensile stress was 550 MPa in the longitudinal direction and 567 MPa in the transverse direction and did not change after irradiation.

Thus, it was shown the possibility of using an electron beam of submillisecond duration for finishing the surface of metal products manufactured by electron beam surfacing. For 308LSi stainless steel, the optimal irradiation modes were determined and the effect of pulsed electron-beam surface treatment on the mechanical, tribological and strength properties of the specimens was shown.

Figure 2. Results of tensile tests of 308LSi stainless steel specimens after pulsed electron-beam treatment (mode No. 1 + No. 2 (20 J/cm$^2$)) in comparison with the initial specimens for different tensile directions relative to the surfacing plane.
4. Conclusion
A method for finishing the surface of metal products made by sequential electron-beam surfacing is presented, which consists in modifying the surface with an intense low-energy electron beam of submillisecond duration. On the example of 308LSi stainless steel, the results of such processing are demonstrated, the optimal modes of exposure are determined. It is shown that as a result of pulsed electron-beam processing, a homogeneous polycrystalline structure without cracks is formed on the surface with unchanged, relative to the initial material, elemental composition, strength (microhardness) and tribological (wear rate) properties. In this case, the roughness of the surface is reduced to 2.1 times in the longitudinal direction, to 5.2 times in the transverse direction. Tensile tests of specimens showed anisotropy of mechanical properties depending on the direction of tension relative to the surfacing plane. After electron-beam processing, the ductility of the specimens in the longitudinal direction increases on 10.6%, and does not change in the transverse direction. This method of finishing, depending on the required tasks, can be used both after preliminary machining and immediately after the manufacture of the product by the method of electron beam surfacing.

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