

Formation of residual stresses in the surface layers of corrosion-resistant steel samples after irradiation with high-current pulsed electron beams

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Abstract. In this paper, the level of residual surface stresses of 15-5PH steel samples manufactured using additive technology before and after heat treatment is analyzed. The research was carried out by layer-by-layer electrochemical etching of stressed metal layers from the sample surface. As a result of the tests, the parameters of the distribution of surface technological residual stresses of the 1st kind (sign, magnitude, depth of occurrence) were obtained. In addition, it is shown that irradiation with high-current and pulsed electron beams affects the level of surface residual stresses and depends on the presence of post-processing operations with or without machining after growing samples by selective laser melting.

Keywords: selective laser melting, high-current pulsed electron beams, post-processing, residual surface stresses.

1. Introduction

In the aircraft industry, when designing and manufacturing responsible products, one of the regulated parameters that are specified in the design and technological documentation is the level of residual stresses of the 1st kind.

Reducing the weight of a gas turbine engine (GTE) is aimed at saving fuel and reducing harmful emissions during the operation of future products. One of the main tasks solved in the aerospace industry is the design of gas turbine engine parts with a smaller mass while maintaining their functionality and physical and mechanical properties.

Modern software allows you to optimize the geometry of the part, which leads to an effective reduction of its mass.

But it is sometimes impractical to use optimization methods in the traditional production of gas turbine engines. The reason is that the creation of products of complex geometry requires a lot of labor and material investments.

Selective Laser Melting (SLM) technology makes it possible to obtain a complex structure in one step, and the complexity of the structural elements does not affect the cost of the product. At the same time, the production of products designed to be manufactured using "traditional" technology reduces the effectiveness of the use of additive methods due to the excessive use of the material.

It turns out that lightweight parts not only improve the characteristics of the gas turbine engine, but also increase the productivity of additive technology.

Despite the declared advantage of additive technologies, the same difficulties arise in SLM technology as in foundry processes, namely, the presence of discontinuities in the body of the part or sample, warping and residual stresses.

High-precision layer-by-layer fabrication using selective laser melting of parts of complex external and internal geometry and having high requirements for both the surface condition and the internal state of the main material of the part, the magnitude of such defects in the manufacture of modern aircraft engine parts requires preliminary full-scale testing of the technology, the choice of a specific location of the part in the installation, the design of a system of additional supports, the choice of technological regime in order to minimize defects, as well as the use of innovative technologies for post-processing.

The influence of high-current electron beams in previous works [1–3] on the roughness, topography, and modification of the surface layers of parts obtained by traditional methods was

analyzed, taking into account the issues of post-processing and the formation of residual stresses in the surface layers of parts obtained by SLM methods. After that, it was proposed to irradiate using radiation technologies as a tool for post-processing parts obtained by additive technologies from various metallic materials.

This article is devoted to the results obtained during these experiments, namely, the change in the level of residual stresses depending on the conditions for obtaining the part (the method of machining and cutting modes, or its absence, as well as the presence of heat treatment in the technological process).

2. Experimental setup

Samples obtained by the SLM method from stainless steel of the 15–5 PH type were used as objects of research. The samples had different shapes: cylindrical (surface without machining) and in the form of plates (surface after milling). The level of residual surface stresses was assessed immediately after growing samples in the case of cylindrical samples and after growing and manufacturing samples by milling in the case of flat samples.

Type 15–5 PH is a stainless, martensitic and quenchable Cr-Ni-Cu steel with high strength and ductility, as well as good weldability and formability. Typical applications are medicine, automotive and aerospace industries. Due to annealing in solution and subsequent aging, the strength increases. Steel 155 PH is applicable in the temperature range from 200 °C to 300 °C.

Further, the assessment of the level of surface residual stresses after heat treatment was carried out in accordance with the mode: annealing at 525 °C for 4 hours in a vacuum, followed by cooling with a furnace. Then the surface was subjected to post-processing using STEP on the Geza MMP accelerator in the following mode:

- first mode (for a flat sample before and after heat treatment): energy density of 30 J/cm² – 2 pulses;
- second mode (for a cylindrical sample, before and after heat treatment): energy density of 30 J/cm² – 4 pulses.

Conducting studies to assess the effect of irradiation with the help of high-current pulsed electron beams (HPEB) on the surface of samples for the presence of surface residual stresses according to the method of N.N. Davidenkov, by layer-by-layer electrochemical etching of stressed metal layers from the sample surface on the SRS-01 complex.

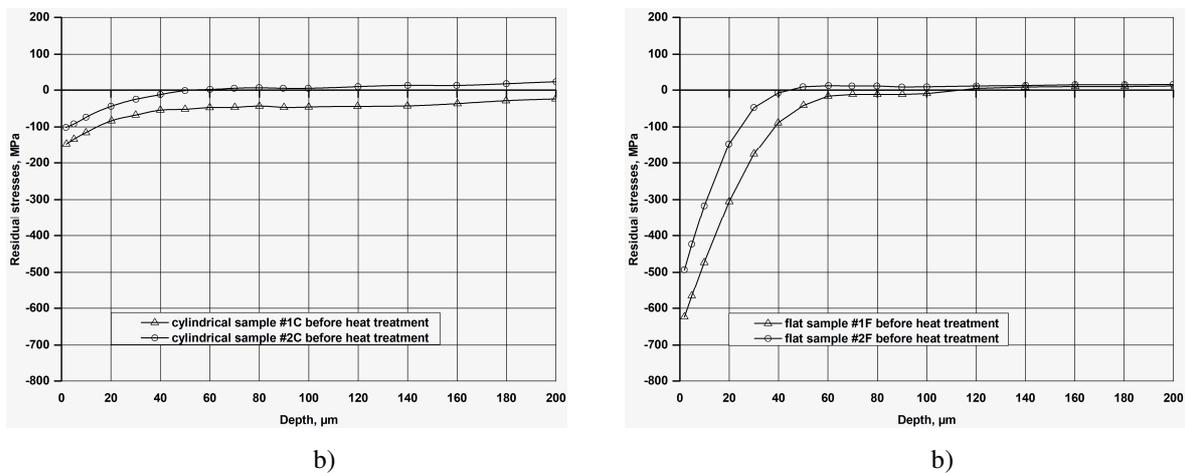


Fig.1. The level of residual stresses depending on the depth of their occurrence before heat treatment: a) for cylindrical samples; b) for flat samples.

3. Results and discussion

3.1. Surface residual stresses in 15–5 PH steel samples before and after heat treatment

In Fig.1 and Fig.2 show the dependences of the level of residual stresses on the depth of their occurrence before and after heat treatment, and Table 1 shows the numerical values of the data obtained during the test.

On steel samples "cylinder" and "flat sample" 15–5 PH before heat treatment without irradiation, the maximum residual compression stresses of the average value are 558 MPa, the value of the sublayer tensile stresses is 18 MPa.

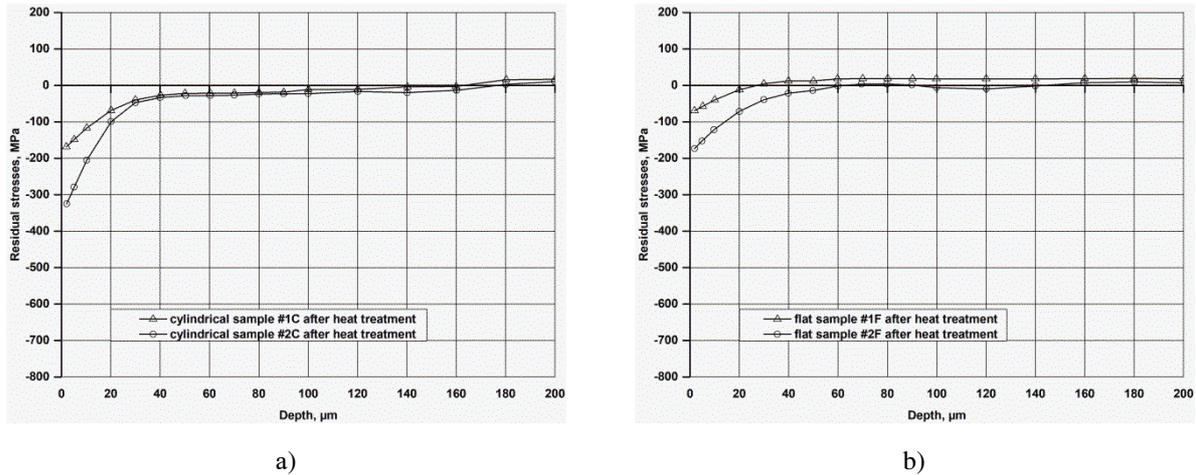


Fig.2. The level of residual stresses depending on the depth of their occurrence after heat treatment: a) for cylindrical samples; b) for flat samples.

Table 1. Values of the residual stress level of samples before and after heat treatment

| Depth, microns | Surface residual stresses of the "cylinder" sample before heat treatment, MPa, Sample No. | | Surface residual stresses of a "flat" sample before heat treatment, MPa, Sample No. | | Surface residual stresses of the "cylinder" sample after heat treatment, MPa, Sample No. | | Surface residual stresses of a "flat" sample after heat treatment, MPa, Sample No. | |
|-------------------|---|------|---|------|--|------|--|------|
| | 1C | 2C | 1F | 2F | 1C | 2C | 1F | 2F |
| | 2 | -141 | -98 | -622 | -493 | -172 | -326 | -68 |
| 5 | -128 | -87 | -564 | -423 | -152 | -279 | -55 | -152 |
| 10 | -108 | -70 | -471 | -315 | -121 | -206 | -36 | -119 |
| 20 | -77 | -41 | -302 | -145 | -73 | -101 | -8 | -69 |
| 30 | -60 | -20 | -171 | -45 | -45 | -49 | 8 | -37 |
| 40 | -48 | -6 | -85 | -2 | -32 | -34 | 16 | -19 |
| 50 | -45 | 3 | -36 | 11 | -27 | -31 | 16 | -10 |
| 60 | -40 | 8 | -12 | 14 | -26 | -30 | 21 | 2 |
| 70 | -40 | 10 | -6 | 15 | -26 | -28 | 22 | 6 |
| 80 | -37 | 11 | -5 | 14 | -25 | -26 | 22 | 6 |
| 90 | -39 | 10 | -5 | 12 | -25 | -24 | 22 | 3 |
| 100 | -39 | 10 | -3 | 12 | -16 | -24 | 22 | -2 |
| 120 | -36 | 15 | 9 | 16 | -15 | -19 | 21 | -5 |
| 140 | -35 | 17 | 17 | 14 | -10 | -22 | 22 | 0 |
| 160 | -30 | 18 | 15 | 17 | -7 | -16 | 22 | 11 |
| 180 | -22 | 23 | 15 | 17 | 10 | 0 | 21 | 12 |
| 200 | -16 | 29 | 17 | 18 | 11 | 8 | 22 | 11 |

On steel samples "cylinder" and "flat sample" 15–5 PH after heat treatment without irradiation, the maximum residual compression stresses of the average value are 249 MPa, the value of the sublayer tensile stresses is 17 MPa.

3.2. Surface residual stresses in 15–5 PH steel samples after training with high-current pulsed electron beams

Fig.3 and Fig.4 show graphs of the dependence of the depth of occurrence of residual stresses on the depth of their occurrence after modifying the surface of the samples after irradiation with high-current pulsed electron beams in accordance with the prescribed modes.

On steel samples "cylinder" and "flat sample" 15–5 PH before heat treatment with irradiation, the maximum residual compression stresses of the average value are 581 MPa, the value of sublayer tensile stresses is 144 MPa.

On steel samples "cylinder" and "flat sample" 15–5 PH before heat treatment with irradiation, the maximum residual compression stresses of the average value are 683 MPa, the value of sublayer tensile stresses is 98 MPa.

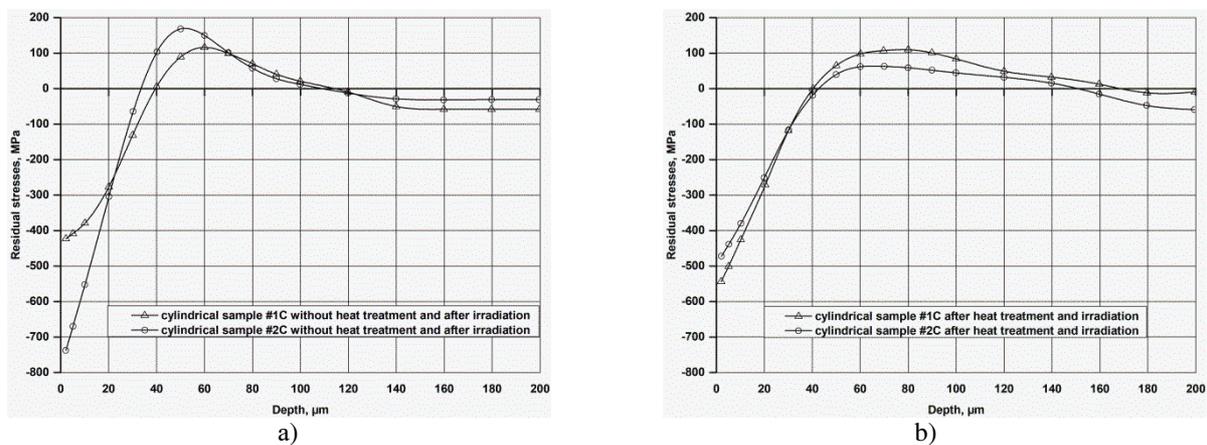


Fig.3. The level of residual stresses depending on the depth of their occurrence of cylindrical samples after irradiation according to mode 2: a) without heat treatment and after irradiation, b) after heat treatment and irradiation.

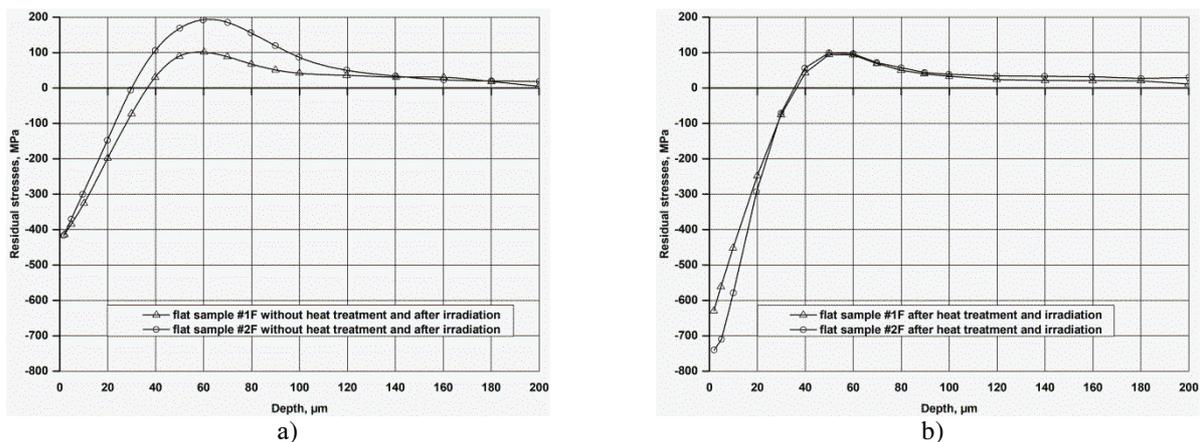


Fig.4. The level of residual stresses depending on the depth of their occurrence of flat samples after irradiation according to mode 1: a) without heat treatment and after irradiation, b) after heat treatment and irradiation.

Table 2 shows the numerical values obtained when assessing the level of residual surface stresses.

Table 2. Values of the level of residual stresses of samples after irradiation of the HPEB

| Depth, microns | Surface residual stresses of the "cylinder" sample before heat treatment, (2 mode: 30 J/cm ² – 4 imp) MPa, Sample No. | | Surface residual stresses of the sample "cylinder" after heat treatment, (2 mode: 30 J/cm ² – 4 imp) MPa, Sample No. | | Surface residual stresses of the "flat" sample before heat treatment (1 mode: 30 J/cm ² – 2 imp), MPa, Sample No. | | Surface residual stresses of the "flat" sample after heat treatment (1 mode: 30 J/cm ² – 2 imp), MPa, Sample No. | |
|-------------------|---|------|--|------|---|------|--|------|
| | 1C | 2C | 1C | 2C | 1F | 2F | 1F | 2F |
| | 2 | -422 | -740 | -543 | -468 | -418 | -415 | -627 |
| 5 | -408 | -672 | -500 | -435 | -383 | -372 | -560 | -710 |
| 10 | -378 | -554 | -425 | -378 | -324 | -301 | -450 | -580 |
| 20 | -275 | -305 | -269 | -248 | -200 | -152 | -247 | -292 |
| 30 | -129 | -64 | -117 | -115 | -74 | -10 | -74 | -73 |
| 40 | 8 | 106 | -3 | -14 | 29 | 100 | 45 | 54 |
| 50 | 93 | 170 | 64 | 42 | 87 | 165 | 97 | 98 |
| 60 | 118 | 152 | 96 | 63 | 99 | 188 | 95 | 94 |
| 70 | 103 | 103 | 108 | 65 | 85 | 180 | 72 | 73 |
| 80 | 72 | 59 | 110 | 60 | 65 | 152 | 52 | 55 |
| 90 | 43 | 30 | 101 | 53 | 49 | 116 | 41 | 44 |
| 100 | 23 | 13 | 84 | 46 | 39 | 83 | 36 | 38 |
| 120 | -6 | -10 | 48 | 34 | 32 | 45 | 28 | 34 |
| 140 | -48 | -28 | 32 | 17 | 28 | 31 | 24 | 34 |
| 160 | -55 | -31 | 12 | -13 | 26 | 20 | 23 | 31 |
| 180 | -55 | -31 | -13 | -47 | 18 | 16 | 22 | 27 |
| 200 | -57 | -31 | -10 | -59 | 3 | 14 | 13 | 30 |

4. Conclusion

The analysis of the data obtained showed that the level of residual stresses in the surface layer is quite sensitive to various processing methods, including thermal and HPEB irradiation.

After heat treatment, there is a clear relaxation of residual stresses for samples after mechanical processing. It should be noted that, unlike samples obtained by the traditional manufacturing method.

The level of residual stresses of the studied samples (obtained with the help of additive technologies) after irradiation have high rates of compressive stresses. Moreover, for irradiated samples after heat treatment after milling is higher.

Acknowledgement

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5. References

- [1] Bytsenko O.A., Filonova E.V., Markov A.B., Belova N.A., *Electronic Journal*, 6(42), 2016; doi: 10.18577/2307-6046-2016-0-6-10-10 (in Russian).
- [2] Teryaev D.A., et al., *J. Phys.: Conf. Ser.*, **1115**(3), 032059, 2018; doi: 10.1088/1742-6596/1115/3/032059
- [3] Teryaev D.A., et al., *J. Phys.: Conf. Ser.*, **1713**(1), 012045, 2020; doi: 10.1088/1742-6596/1713/1/012045