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RECONDITIONING REPAIR OF STEAM TURBINE BLADES USING ADDITIVE TECHNOLOGY

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ABSTRACT

It is rational to use additive technology to perform repair of critical structural elements, which include titanium alloy blades of powerful steam turbines, that is due to high requirements to product quality, namely the need to ensure the required microstructure and mechanical properties of blade material, as well as a low level of the residual stress-strain state and oxidation of material surface. Application of mathematical modeling methods based on computer technologies allows reduction of the scope of experimental studies and ensuring the required quality of repair, which guarantees a certain reliability and serviceability of the blades after repair.

KEYWORDS: steam turbine, blade, titanium alloy, reconditioning repair, additive technology, electron beam surfacing, computational prediction

INTRODUCTION

Five powerful steam turbines of K-1000-60/3000 type are operating in Ukrainian NPS. In them the blades of the last stages of low pressure cylinders (LPC) are exposed to wet steam environment and erosion damage (Figure 1). This factor reduces the residual service life of the blades from titanium alloy, leads to possible shutdowns and accidents in turbounits. The conducted set of studies [1, 2] resulted in determination of the mechanical properties, their possible degradation and fatigue limit of blade material under the conditions of long-term operation. Extension of the service life of 5th stage blade of LPC of K-1000-60/3000 turbines under the conditions of wet steam erosion is a relevant problem now.

Analysis of currently available means of extension of the life of titanium alloy blades under the conditions of wet erosion and vibration loads [1] showed that the safe operating life of the blades of the last stage of the turbine LPC can be extended based on rejection criteria and under the conditions specified below:

● by chord size: in keeping with [3], after removal of erosion wear of the leading edges of blades from TS5 titanium alloy, control by etching method should be performed; limiting size of profile chord in eroded sections, which requires blade replacement, when it has been reached (with allowable delay of not more than 1 year in the case of absence of a replacement blade) — 130 mm;

● by shroud state: repair is required in the case of development of wear (gaps) of more than 1 mm in the contact surfaces as well as cleavages and chipping;

● by operating time: for blades from TS5 titanium alloy the permissible service life is 100 thou h.

Note that the criterion for blade rejection by operating time is too conservative. Experience shows that blades, with more than 180 thou h operating time (SE KhNPS) have been in service almost two times longer than the service life allowed by the manufacturer.

In addition, the manufacturing plant of K-1000-60/3000 type turbines provided to the operators the technological process of repairing the defects on LPC 5th stage blades by arc welding on of inserts with subsequent scraping and control of the welding areas. The recommended modes of nonconsumable electrode gas-shielded (argon) welding without filler material were as follows: tungsten electrode d = 2 mm; current of 50–80 A, straight polarity, argon flow rate of 8–10 l/min.

Thus, to sum up the above-said, the blade service life can be extended, if:

● limiting size of blade chord in eroded sections is not less than 130 mm;

● wear (gap) in the shroud contact surfaces of less than 1 mm, no spallation or chipping;

● repair has already been performed with removal of erosion on blade edges and wear on shroud contact surfaces, using machining in the case, when the chord size after repair is not smaller than the limiting one, or with application of inserts, made by the technology of nonconsumable electrode argon-arc welding.

However, the manufacturing plant did not provide any substantiation for ensuring a low level of total blade deformations during repair by argon-arc welding and sufficient level of blade material fatigue resistance in the melting zone and the HAZ.

Figure 1. Erosion wear of a blade of the last stage of K-1000-60/3000 steam turbine LPC: *a* — general view of 5th stage; *b* — defect of blade edge erosion wear

A promising approach is repair of titanium alloy blades of K-1000-60/3000 turbines, using modern technologies of layer-by-layer formation by electron beam deposition in vacuum chambers, which can ensure a low level of residual shape deformations, as well as the required microstructure and mechanical properties of blade material.

THE OBJECTIVE OF THE WORK

is to show the possibility of reconditioning repair of titanium alloy blades of steam turbines, using additive technology of electron beam deposition in vacuum chambers, which can provide the required mechanical properties and geometrical accuracy of the product, compared to application of argon-arc welding.

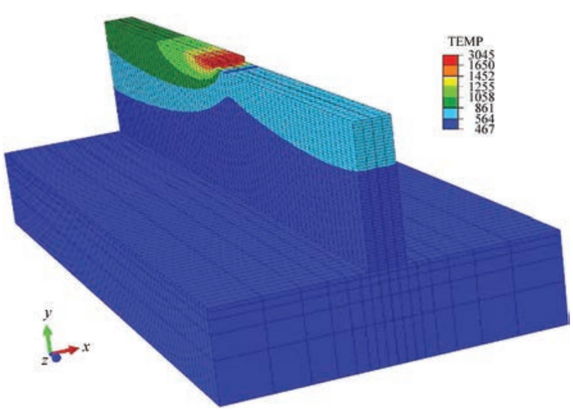

Figure 2. Results of calculation of temperature distribution in a tee sample during layer-by-layer formation of the part [5]

RECONDITIONING REPAIR TECHNOLOGY

Technology of repair surfacing of K-1000-60/3000 turbine LPC 5th stage blades with erosion damage should include the following stages:

1. Machining of erosion wear zone with damaged metal removal.
2. Multilayer electron beam surfacing of the wear zone to restore the initial dimensions.
3. Heat treatment (general) of the blade to form the required metal structure and lower the residual stress level.
4. Machining to sizes and roughness of blade surface specified in the design documentation.
5. Protective coating deposition (option) [4].

The most complicated is stage 2 of the proposed technology, namely multilayer electron beam surfacing of the wear zone to initial dimensions in vacuum chambers, as it is necessary to ensure a low level of residual shape deformations and stresses of the blade, as well as the required microstructure and mechanical properties of blade material. To analyze this issue, finite element modeling of this technological operation was performed on a model of a tee-sample of a limited size and on full-scale blade model.

INVESTIGATIONS OF THE FEATURES OF THE INFLUENCE OF TECHNOLOGICAL PARAMETERS OF LAYER-BY-LAYER SURFACING ON THE TEE SAMPLE RESIDUAL STATE

Layer-by-layer electron beam surfacing of a sample from VT6 titanium alloy by stringer beads of 3 mm width and approximately 0.5 mm thickness was considered. Surfacing speed was 14 mm/s. The results of solving the task of nonstationary heat conductivity showed that the temperature field kinetics at layer-by-layer formation of the tee sample on a substrate of 6×30×70 mm dimensions, which simulates the blade body in terms of heat conductivity and rigidity of the structure, has an essentially three-dimensional nature (Figure 2) [5].

As proved by calculation results, this process is characterized by rather high cooling rates (160–660 °C/s). In keeping with the diagram of microstructural transformations of VT6 alloy, a martensitic microstructure with α″-phase content forms in the deposited material of the tee sample [6]. According to calculation data, grain of 180 μm size forms in the material of the first layer, where the highest cooling rate was achieved due to the presence of a massive cold substrate, and in the points at formation of the 5th and 20th layers, where the material is deposited on the already heated sample, the grain size is much larger — 300–450 μm.

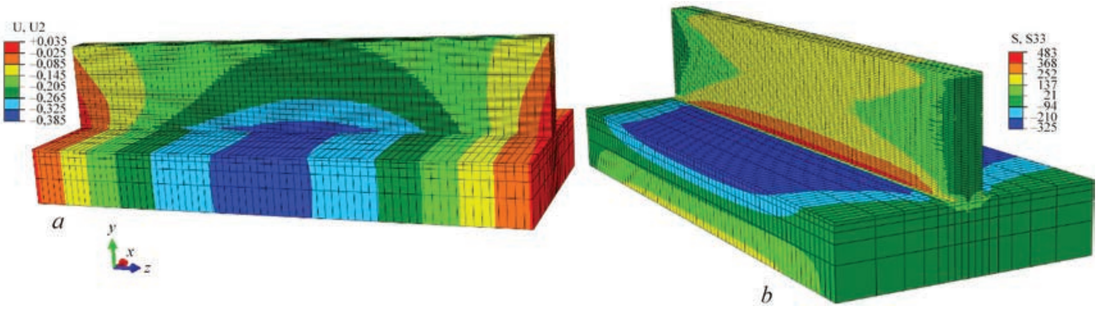

Figure 3. Results of calculation of residual stress-strain state in a tee sample [5]: *a* — longitudinal deflection; *b* — longitudinal stresses

Technological parameter of delay time Δt between bead deposition (Figure 4, *a–c*) has an essential influence on the cooling rate and grain size, and, as a result, on the part material yield limit [6]. It is seen that better mechanical characteristics and more homogeneous material structure were determined in the sample, made with greater time Δt, while insufficient time between bead deposition of $\Delta t = 10$ and 15 s results in upper layer material with a low yield limit and grain heterogeneity by height. However, a too long interpass time (65 s) leads to an excess of α'-structure, and, hence, it lowers the material ductility, compared to shorter interpass time. Thus, it is rational to consider the use of substrate preheating at $\Delta t = 29$ s. Substrate preheating makes the lower layer structure more homogeneous and essentially improves the material ductility.

FINITE ELEMENT MODELING OF ELECTRON BEAM SURFACING OF THE BLADE

A finite element model of 5th stage blade of K-1000-60/3000 turbine LPC was developed, where repair surfacing of the material (TS5 or VT6 titanium alloy) is modeled in the characteristic erosion zone, namely in the blade upper part of 100 mm length. Surfacing mode is similar to modes for tee samples. Surfacing zone height is taken to be equal to 10 mm, which corresponds to maximal level of the depth of blade erosion damage. It is envisaged that before surfacing, machin-

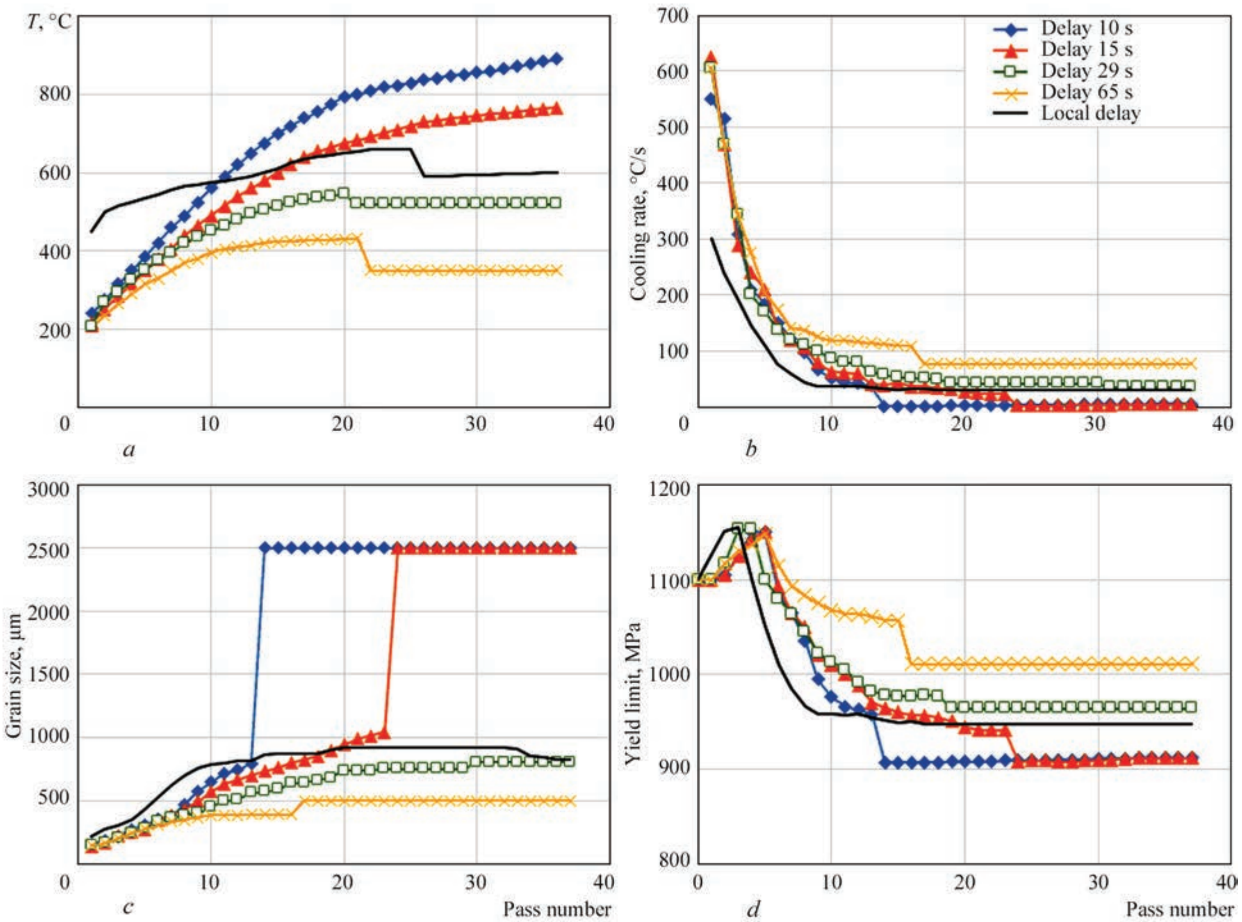

Figure 4. Dependence of temperature in a point before the next layer deposition (*a*), cooling rate (*b*), grain size (*c*) and material yield limit (*d*) on pass number for different interpass delay times [6]

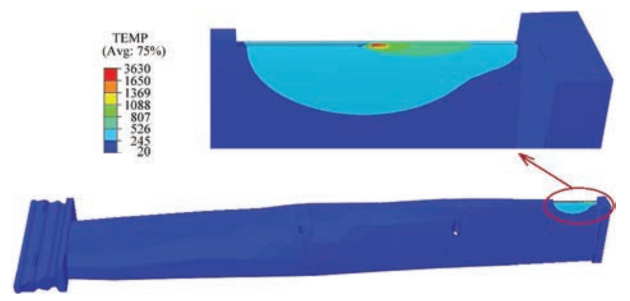

Figure 5. Temperature distribution during electron beam surfacing

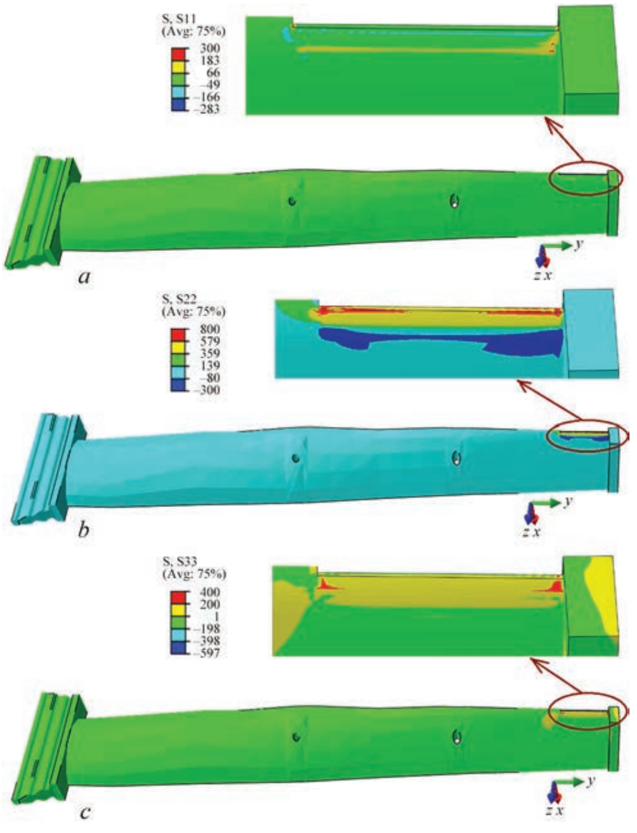

Figure 6. Residual stress distribution: *a* — σ_{xx} component by deposit height (σ_{xx} = 150–300 MPa); *b* — σ_{yy} longitudinal component (σ_{yy} = –300–800 MPa); *c* — σ_{zz} transverse component by blade thickness (σ_{zz} = –200–400 MPa)

ing of the erosion damage zone is performed with removal of blade material to the depth of 10 mm. The objective of mathematical modeling is prediction of residual level of the stressed state and total deformations of the blade shape change, as well as the material structural state in the surfacing zone, which can be used for selection of the optimal technological parameters of repair surfacing. Considering the overall dimensions of the blade (length of 1200 mm), it is possible to perform general (furnace) heat treatment after surfacing, in order to lower the residual stress level and produce a more homogeneous structure of the material.

Figure 5 shows the calculated temperature distribution during electron beam surfacing of the blade. In the surfacing mode with 29 s pauses between the layers, the material of the zone of reconditioning re-

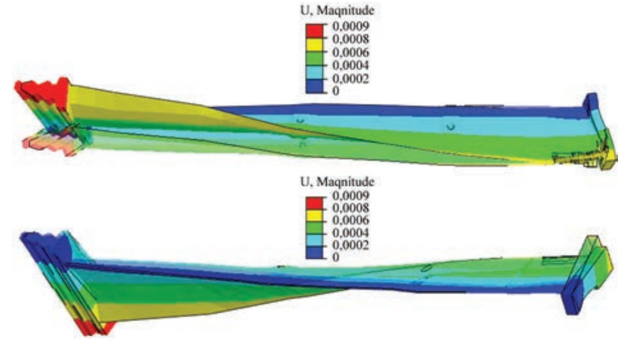

Figure 7. Blade residual deformations (torsional), up to 0.9 mm value of maximal displacements

pair of the blade is heated up to the temperature of 250–500 °C.

Total deformations of the blade shape change remain to be a critical parameter for the repair surfacing technology. Analysis of the obtained results of the numerical experiment (Figures 6, 7) on repair surfacing of the blade in the erosion damage zone showed that:

- Rather high residual stresses (longitudinal component) form in the surfacing zone (locally), on the level of the titanium alloy yield limit (up to ≈ 800 MPa).
- After surfacing undesirable total residual deformations of the blade (torsional) are predicted, the value of maximal displacements is up to 0.9 mm.
- Modeling of the general heat treatment in the furnace can show an essential lowering of the residual stresses (positive effect) and increase of the blade total deformations (negative effect).

An important issue of the technology of repair surfacing of critical structural elements is ensuring a low level of the deposited material damage during manufacture and determination of the requirements to permissible defect dimensions. As regards manufacturing using the technology of layer-by-layer formation by electron beam surfacing of T-beam structures, it was shown by numerical studies of brittle strength [7] that the required resolution of non-destructive testing is equal to approximately 0.5 mm, which ensures a strength margin of not less than $n = 2$, while maintaining the required conditions of the temperature mode of product formation, in terms of providing the required structure and mechanical properties of blade material.

CONCLUSIONS

1. An approach is proposed to repair of titanium alloy blades of a powerful steam turbine K-1000-60/3000, using additive technology of layer-by-layer formation, in order to restore the initial geometry by electron beam surfacing in vacuum chambers.

2. Results of finite element modeling showed the fundamental possibility of ensuring a low level of residual shape deformations, as well as the required

microstructure and mechanical properties of blade material after reconditioning repair, using additive technology of layer-by-layer formation. However, it is rational to perform general heat treatment, in order to lower the residual stress level and to ensure a high homogeneity of the material structure and mechanical properties in the repair zone.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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