ASSESSMENT OF THE EFFECTIVENESS OF REPAIR TECHNOLOGIES FOR POWER PLANT OPERATION*

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Tendencies in development of repair technologies in service of gas turbine engines (GTE) are considered. A procedure was developed for qualitative assessment of the influence of part repair technologies on the set of mechanical characteristics of base material in the repair zone. The effectiveness of the technology is determined by the change of mechanical properties.

Keywords: *power plants, repair technologies, gas turbine engine parts, mechanical properties*

Modern tendencies in development of gas turbine construction consist in creation of a service system simultaneously with development of new engines [1]. The most effective element of this system is introduction of advanced technologies of corrective maintenance to extend the operation period with setting up of specialized centers of engine repair. In the USA repair of aircraft equipment is performed by engine manufacturers, large independent repair companies, as well as subdivisions of major carriers [2]. According to predictions, sales of new Boeing aircraft in the next 20 years will amount to 1.7 trln USD, and service income will be 3.1 trln USD. And half of this sum will come from repairs. In 2000 repair income was equal to 44.6 bln USD, and by 2002 it will rise to 110 bln USD [2].

At present the segment of GTE manufacturers in engine service and repair sector is growing. Rolls-Royce has 300 major customers in 50 countries [3, 4], and promotes establishment of subsidiaries specializing in repair. Company's annual contracts amount to 9 bln USD.

GE is developing new repair technologies [5], also for the USA [6], Alstrom is creating CLE system envisaging application of new repair technologies to increase GTE overhaul periods [7]. Leading companies are building enterprises for power equipment repair in different regions of the world [8]. Repair routine for an industrial GTE is being patented [9]. Starting from 2000, Trans Canada Turbines has provided GTE overhaul service. In the next 10 years the sum of orders for repair of GTE of RB 211 type will exceed 250 mln USD [10]. Ever more attention is given to development of repair technologies and repair personnel training [11] in prediction of repair costs [12].

A key issue of repair technologies remains to be assessment of residual life and its extension, so that a number of studies are devoted to development of procedures and mathematical models of damage medium mechanics for theoretical analysis of the processes of life exhaustion of structural element materials, allowing for degradation processes developing under operation conditions [13, 14]. Comparison of strength analysis results with structural changes in the metal proceeding in high-temperature service, allows determination through calculations of the most probable sites of damage accumulation [15].

Practical repair and reconditioning of power equipment components makes use of a broad range of modern technologies. For GTE blade repair MTU Aero Engines GmbH patented a combination of the methods of powder metallurgy, welding and machining of the weld area [16], as well as a repair technology of brazing with nickel alloy based brazing filler metals [17]. The methods of efficient and rational application of brazing for repair of defective blades of GTE hot stage and the main technologies developed for these purposes, are given [18, 19]. Cut-out defective sections are filled with molten powder material, consisting of the braze alloy and filler by argon microplasma spraying [20]. Techniques of laser welding up of defects and laser cladding for repair of spot defects in different combinations of heat and finish treatment are becoming ever wider accepted in practice [21–27].

It is difficult to repair parts from high-temperature nickel alloy with high aluminium and nickel content by regular welding processes. Therefore, the method of electrospark alloying using high-strength filler is promising for repair of unweldable alloys. It is noted [28] that mechanical properties of the repaired section are quite satisfactory, but introduction of the technology of electrospark alloying into industry will require certain efforts in the future. IHI and Mitsubishi developed a new method of electrospark alloying, namely micro spark coating (MSC) [29] for GTE blade repair, which uses the energy of highly-sensitive microelectric discharges, and can replace the traditional repair techniques in a number of cases, namely

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welding, galvanic, and thermal. Toshiba developed method of hot isostatic pressing (HIP) for reconditioning of GTE blades [30]. Extension of the service life of a part with some fatigue damage is achieved with ion nitriding technology [31].

New integrated technological processes of GTE blade repair, combining various operations, are becoming accepted. Processes of welding and subsequent local heat treatment by the electron beam are efficient [32]. Snecma Moteur SA applies cold rolling after welding of the defective section of blade airfoil. This induces residual compressive stresses in the blade airfoil, which compensate the residual tensile stresses in the weld, thus achieving strengthening of the reconditioned structure. This technique is effective for repair of solid discs with blades, when individual blades cannot be removed for replacement or reconditioning [33].

Most of the repair technologies should be regarded as alternative. In this connection it is necessary to develop procedures of technology assessment and selection.

The effectiveness of repair technologies can be evaluated primarily by the change of the set of mechanical properties of the repaired defect zone compared to properties of unrepaired zone [34].

The purpose of this study is development of the procedure of quantitative assessment of the influence of repair technologies on service properties of base material in the repair zone.

Experimental procedure. Samples from undamaged material and samples with repaired defects — simulators of real damage made from models of GTE blades from EK-9 alloy — were used to perform a series of studies of the influence of the features of repair technology on the characteristics of short-time and long-time static strength, as well as high-cycle fatigue. Repair technologies of arc welding and cladding and microplasma powder cladding developed at PWI were used. Samples were made by spark erosion process. After the cladding cycle the samples were heat-treated according to the accepted repair technology. Two-sided notches of 10 × 0.5 mm size were made on side surfaces of the flat sample as damage simulators.

A feature of testing was the fact that deformation not of the entire sample, but just of the damaged area was measured using extensometer with 12 mm measurement base. It was also measured in a similar area of an undamaged sample. Diagrams of deformation of such samples at temperatures of 20 and 800 °C were recorded. Investigations were conducted in INSTRON testing system. Programmed loading, thermal condition control and data processing in the numerical and graphic form were provided in the automatic mode.

Two types of samples of EK-9 alloy were made for high-cycle fatigue testing: cylindrical smooth samples for determination in the initial condition and samples with a raiser of 1 mm depth and 2 mm length along sample generatrix. The raiser simulated a defect to be repaired. A sample supported in cantilever was mounted in an electrodynamic tester. During testing the range of oscillations of the cantilever sample free end corresponding to the required level of stress amplitude, was established. The range was monitored by MBS-2 optical microscope, the number and frequency of loading cycles — by data processing frequency meters ChZ-34.

Assessment of the influence of repair technology on the thermal stress and strain state was performed by design-calculation method. Investigations were conducted on wedge-like samples simulating blade edge. Damaged zone cutting out and subsequent repair microplasma powder deposition of a bead were applied to repair the damaged edge. The level of thermal stress state of wedge-like sample edge after repair depending on the technological modes of testing was assessed in a gas-dynamic bench in keeping with the standard [35]. Calculations of thermal and stress-strain state (SSS) of the repaired samples were conducted using SPACE applied software package [36]. Characteristics of EK-9 (base metal) and EP-539 (deposit metal) alloys were used in calculations. The damage stage was considered, when thermal fatigue cracks of up to 0.5 mm length develop on the edge, and edge building-up to 0.7 mm depth is required, which corresponds to the edge rounding-off radius. Results of thermometering of samples in the tester by fixed thermal cycling modes were the basis for analysis of the kinetics of thermal state and SSS of the material. The most stringent mode of GTE blade operation was used, namely 60 s heating and 60 s cooling in the temperature range of 350–1100 °C.

Results and their discussion. *Short-term and long-term static strength*. Analysis of investigation results allows making the following statements.

Deformation curves obtained on undamaged samples (Figure 1, curve *1*) run somewhat lower (≈ 10 %) than the certificate characteristics of EK-9 alloy. This is indicative of the influence of the processes of model blade manufacturing, which lead to certain deviations of mechanical characteristics. Technology of spark erosion treatment of the samples can have additional influence.

Analysis of deformation curves of the sample test portion in the repaired defect zone (Figure 1, *a*, curve *2*) points to 15 % lowering of limit characteristics of strength and significant lowering (more than 50 %) of the ductility margin. However, sample failure at tension occurs beyond the zone of the repaired defect. Therefore, it may be stated that the developed repair technology ensures recovery of material strength to the level not lower than that of the sound region.

Results of long-term strength testing given in Figure 2 show that the nature of failure of sound and repaired samples is practically identical to the given in Figure 1 results of short-term static testing. Similar to short-term testing, the repair zone in the repaired sample is not a weak link.

Prediction of performance by the criterion of resistance to long-term loading was performed using the base diagram method (BDM) suggested by V.V.

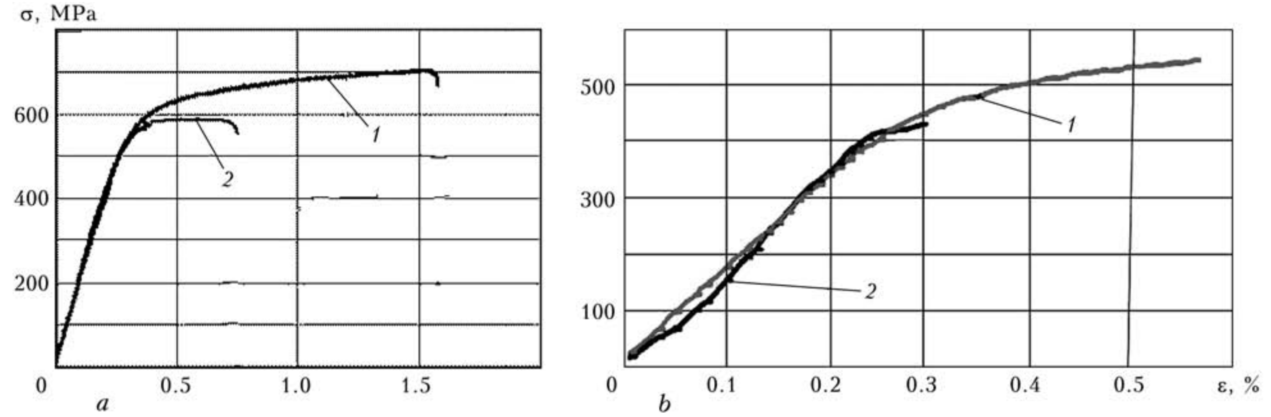


Figure 1. Curves of short-time deformation of a defect-free sample (*1*) and sample with a repaired defect (*2*) at temperature of 20 (*a*) and 800 (*b*) °C

Krivenyuk [37]. This requires information about the behaviour of an analog-material in a certain time interval of prediction; results of static testing (see Figure 1); limited information on the studied material behaviour at long-term loading at a limited cycle number (see Figure 2). If information is available, other data on similar materials as to composition and properties are also used.

Proceeding from the data on the nature of property change allowing for the true scatter of data, coefficients of the base diagram equation were found in the following form:

$$\lg \sigma_t' = \lg \sigma_1 - (3.6 - \lg \sigma_1)(\lg t + 0.11 g^2 t)/12,$$

where σ_t' is the current value of stress in the base diagram, MPa; σ_1 is the stress leading to fracture within 1 h; t is the time to fracture, h.

Features of individual sections of long-term strength curve are precised using experimental characteristics. A fundamental aspect of application of BDM prediction procedure is determination of correction coefficients, which allow for the kinetics of ductility variation. Tentative calculations by BDM procedure demonstrate a lowering of long-term strength characteristics over considerable time base to the level of about 30 % of the initial values.

High-cycle fatigue. Testing of initial samples was conducted at resonance frequency of 850–900 Hz by the first oscillation mode. Endurance limit was determined on the base of $2 \cdot 10^7$ cycles. Number of loading cycles was recorded during testing. Start of lowering of resonance frequency (1), and lowering of resonance frequency by 1 % (2) were taken to be the limit state criterion. The first of them was taken to be the fatigue life, which corresponds to the moment of fatigue crack initiation, which is followed by the process of crack development to the moment of lowering of resonance frequency by 1 %. The latter fatigue life was taken as the sample final fracture. Testing results are given in Figure 3.

Analysis of the curves is indicative of the fact that in terms of cycle number the process of fatigue crack development is 3 to 4 longer than before crack initiation. A feature of fatigue fracture is presence of several cracks on the surface of sample test part.

After application of repair technology the samples were ground. Resonance frequency was 720 Hz. Fatigue curves after application of repair technology are given in Figure 4. Comparison of testing results shows that samples after repair have lower fatigue characteristics than the initial values ($\sigma_{-1} = 240$ MPa — initial; $\sigma_{-1}^{\mathrm{rep}} = 205$ MPa — samples after repair). In addition, whereas the fatigue curve of the initial samples has the shape of an inclined curve up to the number of cycles of $2 \cdot 10^7$, the curve for the repaired samples has a steeper slope and physical fatigue limit equal to $2 \cdot 10^7$ cycles with curve break abscissa on the level of $3 \cdot 10^6$ cycles. Fatigue cracks in samples after repair developed not in the weld zone, but in the HAZ metal.

Obtained results were interpreted in terms of limit exhaustion of ductility in keeping with the model proposed in [38, 39].

Thermal-stress state of materials in the repair zone. The main purpose of work in this direction was assessment of the influence of the difference between

Mechanical properties of EK-9 alloy

Temperature, °C	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	*E*, MPa
20	$\frac{704.2}{597.0}$	$\frac{637.3}{570.0}$	$\frac{1.3}{0.5}$	$\frac{180}{180}$
800	$\frac{630.8}{460.0}$	$\frac{536.0}{450.0}$	$\frac{0.6}{0.3}$	$\frac{153.19}{153.19}$
Note. The numerator gives the initial values, the denominator — values after repair.				

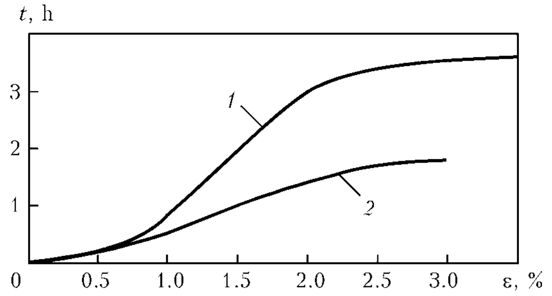


Figure 2. Curves of creep of defect-free samples (*1*) and samples with a repaired defect (*2*) at the temperature of 800 °C

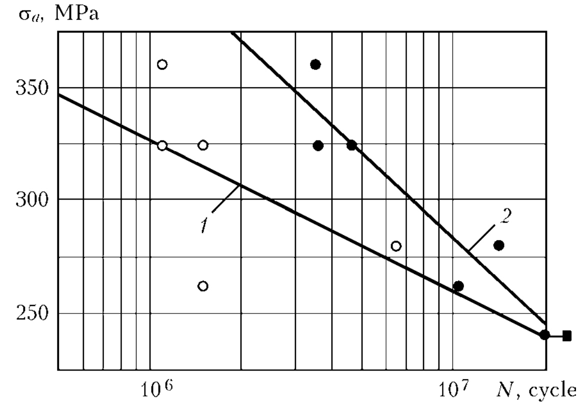


Figure 3. Fatigue curves of samples from EK-9 alloy in the initial state: *1* — start of lowering of resonance frequency; *2* — lowering of resonance frequency by 1 %

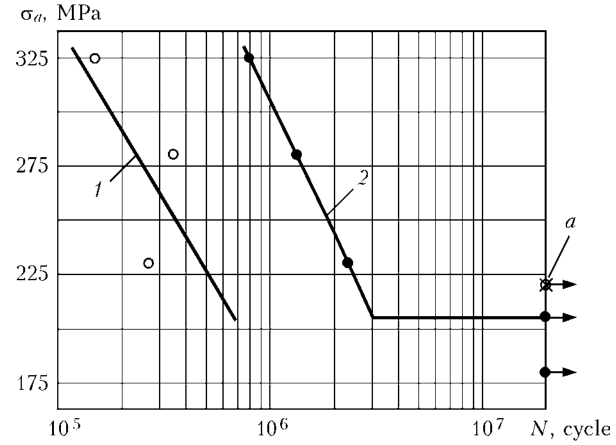
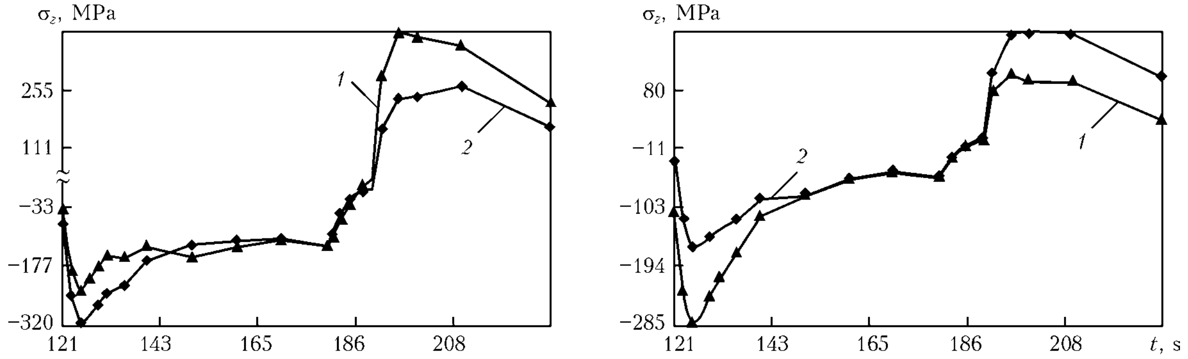


Figure 4. Fatigue curves of samples of EK-9 alloy after repair: *1* — start of resonance frequency lowering; *2* — start of resonance frequency lowering by 1 %; *a* — sample after testing (N = 2·10^7 cycles) first at σ_a = 205, and then at σ_a = 220 MPa



a

b

Figure 5. Variation of stresses σ_z in the point of contact of deposit material (*1*) and base metal (*2*) in the thermal load cycle by condition 1 (*a*) and 2 (*b*)

the properties of the base and deposited metals on the level of residual process stresses and kinetics of their variation under the conditions of variable temperatures.

Predominant attention was given to two variants implemented in practice. In the first model problem an assumption was made that the repair technology ensures absence of residual stresses at the temperature of 20 °C, i.e. at this temperature the initial stresses in the wedge are absent. In the second model problem the initial assumption was that the repair deposit was made at the temperature of 1200 °C and at this temperature and uniform thermal state initial stresses are absent. Generalized results of such analysis are given in Figure 5.

Comparing thermal stress states of the wedge-like sample in the thermal load cycle of the two variants of the initial state of materials in the deposit zone, we can note the following. Higher stresses, both compressive and tensile, arise in the case of variant 1. However, while the compressive stresses in the two variants are close in absolute values, tensile stresses, which are particularly hazardous for initiation and development of thermal fatigue cracks, are much smaller for case 2, which gives a more adequate representation of the actual situation. These stresses are as follows: for variant 1 — 400 (on the edge), 380 (deposit metal) and 245 (base metal), and for variant 2 — 145, 110 and 171 MPa, respectively.

In conclusion it should be noted that in practical operation of power plants, including AGTE, a tendency has emerged, when the scopes of repair and reconditioning operations start exceeding the volume of new equipment sales. This discrepancy will increase with time.

Practical repair and reconditioning operations are performed with application of a wide range of modern technologies. A greater effect of ensuring the required level of properties is achieved when using multioperation integrated technologies. Their effectiveness is determined by the level of lowering of the set of mechanical properties of the reconditioned parts.

CONCLUSIONS

1. A procedure is proposed for qualitative assessment of the influence of repair technologies on the service properties of base material in the repair zone. The procedure uses laboratory, bench and numerical methods determining the characteristics of short-time and long-time static strength, high-cycle fatigue, as well as assessment of thermal stress state of the repair zone.

2. Further studies are required on a multifactorial experiment to determine the optimum technological modes of repair technologies. The set of optimization

criteria should include cost indices. Assessment and prediction of the residual life of reconditioned parts are performed by calculation methods based on experimental laboratory testing.

3. It is necessary to develop standard documents specifying introduction in repair plants of the procedures for determination of the set of mechanical properties, depending on the technological modes.

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