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REPAIR OF LARGE-SIZED BLADES OF THE FAN OF GAS-TURBINE ENGINE*

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The paper presents the results of work on restoration of damaged area of gas-turbine engine fan by welding of a fragment by electron beam process. Fatigue limit σ_{-1} was determined for fan blades for D-36 engine with 16–65·10^3 N thrust repaired by his technology. Metallographic examination of the blades with fragment welding was carried out after fatigue tests. Perspective directions for increase of fatigue limit of repaired fan blades were proposed. 8 Ref., 2 Tables, 9 Figures.

Keywords: *electron beam welding, titanium alloy, fan blades, fragment welding, heat treatment, structure, fatigue limit*

Fan blades are one of the most critical and loaded parts of an aircraft engine. Fan blades are expensive, because of application of individual billets and long cycle of mechanical and heat treatment, polishing and finishing of blades. Therefore, widening the range of blade repair techniques is urgent and economically feasible. The largest number of operational damage of blades is associated exactly with ingress of foreign objects into the engine. It should be noted that most of all blade damage is located in the above-flange part on the leading edge. Fan blade damage lowers engine characteristics, and considerable damage resulting from ingress (for instance, birds), affects flight safety.

Repair documentation in place at JSC «Motor Sich» enterprise envisages certain norms for damage extent, acceptable without correction, as well as repair of damage by such methods as straightening of the leading edge, cleaning and polishing of nicks, cutting damaged sections of the leading edge of not more than 700 mm^2 total area. It should be taken into account that cutting the edges lowers the engine thrust. In the cases, when damage exceeds those allowed by repair documentation, the parts are rejected.

JSC «Motor Sich» tried out the technology of repair of D-36 engine fan blades from two-phase titanium alloy VT3-1 by electron beam welding (EBW) of a fragment instead of the damaged section with subsequent determination of the fatigue limit σ_{-1}. The technology is based on our enterprise experience [1], as well as allowing for the experience of other enterprises on reconditioning repair of elements and assemblies of gas-turbine engines [2].

Welding technology was first tested on flat samples. Sample welding was performed from two sides in electron beam unit ELU-20, which is fitted with program control of mode parameters, program displacement of electron beam gun and part by assigned coordinates. Welding was followed by two-step heat treatment (HT) of the samples, first step of annealing by the electron beam (EBA), second step in the furnace. Mechanical properties were determined on welded and solid samples, type XIII, to GOST 6996–66. SC «Ivchenko-Progress» performed strength calculations and determined the highest acting stresses in the anticipated areas of weld location. Regions with maximum stresses include the transition from airfoil to antivibration flange and area of the joint of the airfoil with blade root attachment. Calculation results allowed defining the repair zone, weld location (Figure 1) and parameters for further performance of fatigue testing of D-36 fan blades [3]. Bending vibrations in the fourth form were specified for determination of σ_{-1} in the repair zone for fatigue testing.

Optimum configuration of the fragment was developed (Figure 2) and dimensions of run-off tabs (Figure 1, *b*) were determined, taking into account the fact that undercuts can form at EBW on the edges of a blade, which has final dimensions. Fragment material corresponds to the part base material.

Further work was performed on full-scale samples of the blades. Damaged blade areas were cut accord-

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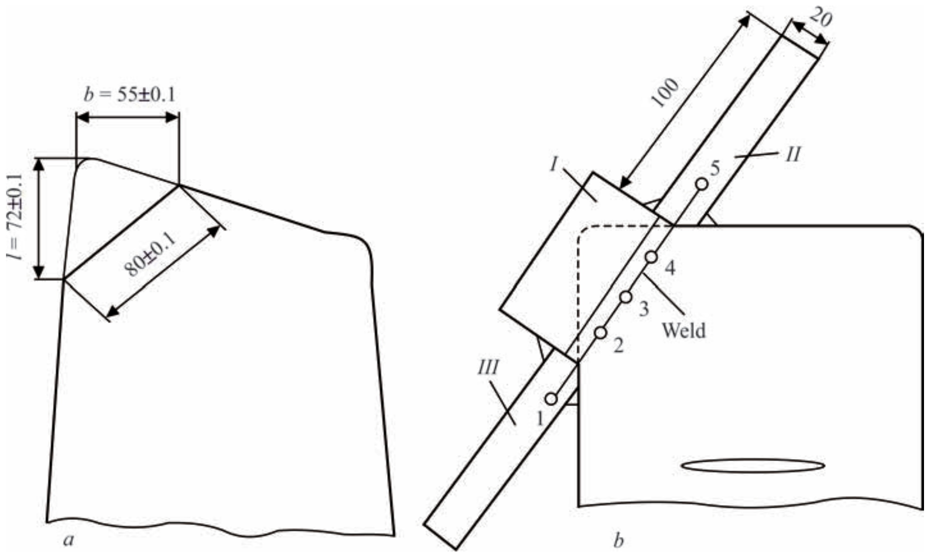

Figure 1. Schematic of calculated zones of repair (*a*) and location of the weld (*b*): *I* — welded fragment; *II*, *III* — run-off tabs; *1–5* — base points of weld division into sections

ing to earlier determined calculated repair zones (Figure 1, *a*; Figure 3, *a*).

In the welding zone the fragment was machined to suit the blade airfoil profile and fitted to ensure repetition of profile configuration, providing a smooth transition and 0.3 mm allowance around the contour from both sides.

Welding of the blade with tack-welded fragment (Figure 3, *b*) was performed by EBW from two sides. The weld was divided into sections by five base points (Figure 1, *b*), with correction of welding modes, depending on the change of the thickness of blade airfoil profile section from 1.2 up to 2.4 mm. Programming of welding mode parameters allowed ensuring sound formation of the weld, and avoiding appearance of defects in the form of burns-through (Table 1).

After blade welding, two-step HT (Figure 3, *c*) was conducted by the following mode: HT first step was performed by EBA in specialized unit Lara-52 at T = 910 °C with 10 min soaking. EBA modes were selected by analogy with other GTE parts from two-phase titanium alloys, and considerably reduced distortion [4]. Second step — furnace annealing — was performed in a shielding atmosphere at T = 650 °C for 3.0–3.5 h.

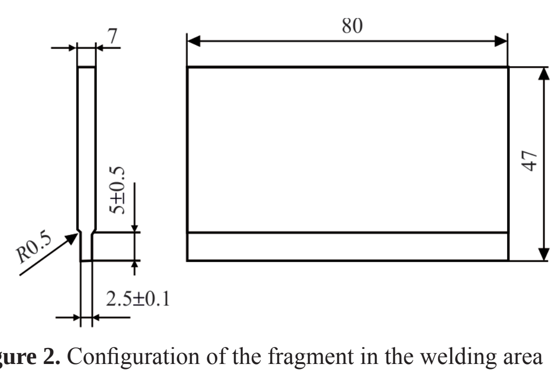

Figure 2. Configuration of the fragment in the welding area

Furtheron, machining of welded fragment was performed up to achieving the required profile configuration with preservation of initial dimensions (Figure 3, *d*). Finished blades were subjected to control of the repaired locations by LYuM1-OV method and to X-ray testing. No defects were found by control results.

Fatigue testing was conducted with determination of σ_{-1} of three batches of full-scale blade samples (Figure 4):

• first batch in the quantity of 8 pcs taken from different engines, having different operating time

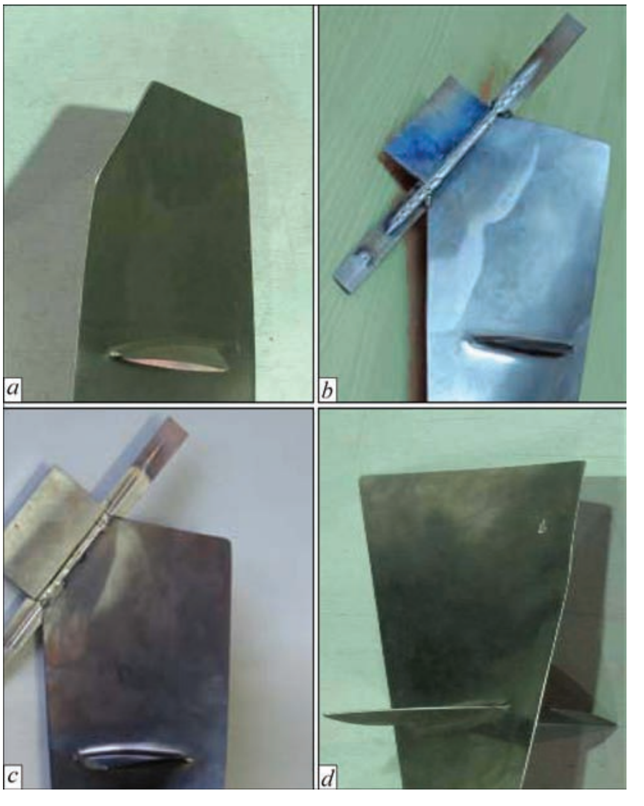

Figure 3. Steps of blade repair performance: *a* — cutting; *b* — EBW; *c* — HT; *d* — machining

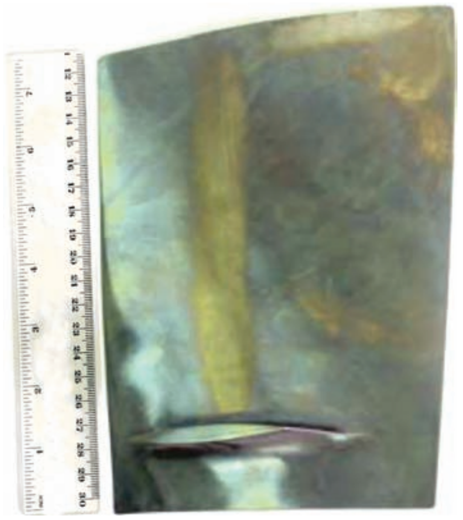

Figure 4. Sample for fatigue testing

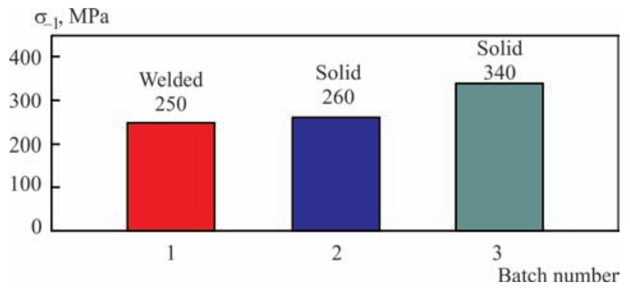

Figure 5. Fatigue limit for three batches of blades

and repaired by welding a fragment (welded) (Table 2). Sample fracture occurred at the stress of 280–340 MPa, after $N = 7.4 \cdot 10^6$ cycles;

- second batch in the quantity of 4 pcs, taken from one engine, with operating period of 3599 h (solid). Sample fracture occurred at the stress of 280–340 MPa, after $N = 7.4 \cdot 10^6$ cycles;
- third batch in the quantity of 6 pcs, taken from one engine, with operating time of 5597 h (solid). Sample fracture occurred at the stress of 370 MPa, after $N = 7.4 \cdot 10^6$ cycles.

Testing was conducted at room temperature and vibrations by the fourth bending form (at the frequency of the order of 1074 Hz), determined by SC

Table 1. EBW modes

Pass number	v_w, m/h	I_w, mA	I_f, mA	U, kV	H, mm
Face side (trough); direction by points 1-2-3-4-5					
1	60	14-18-22-22	630	60	220
Reverse side (back): direction by points: 5-4-3-2-1					
2	60	20-18-13-13	630	60	220

«Ivchenko-Progress» for distribution of the most intensive stresses in the repair zone.

It should be noted that three samples from the batch of blades (welded) failed, two of which with individual (ind.) No.1502F and 1439F had the same operating time and were taken from one engine, despite the fact that their fracture occurred at different testing stress (Table 2). Coarse-grained structure and defects revealed in the weld at metallographic examination, probably, had a negative effect on premature fracture of samples at testing. Lowering of σ_{-1} for the first batch of welded blades is in place relative to the second batch of solid blades, which is within the limit of the error and is equal to 10 MPa. Difference in σ_{-1} between the second and third batches of blades (solid) is equal to 80 MPa (Figure 5), that is, probably, due to unfavorable influence of service factors. Fracture of both the welded and sold blades proceeded in the same manner, in the upper part of blade airfoil edge.

Results of testing solid samples of blades lead to the conclusion that the number of operating hours and the service conditions have a negative effect on σ_{-1}. This intermediate stage was conducted with the understanding that the data on σ_{-1} of blades after operation, could be obtained exclusively by experiment. Unambiguous comparison of σ_{-1} requires testing blades, repaired by welding a fragment, and solid blades by the serial technology with the same operating time (from the same engine).

In order to improve the service properties of parts, repaired by welding, a new idea was proposed of increasing σ_{-1} by application of hardening techniques — surface plastic deformation (SPD) [5]. In view of the complex geometry and high requirements to surface

Table 2. Results of fatigue testing of the first batch of blades (welded) with different operating time

Sample number	Individual part number (ind.)	Operating time SSO/ALR*, h	Testing stress, MPa	Cycle number, $\cdot 10^6$	Note
1	815Ya	8996/4192	340	0.22	Failed
2	355A	3302/13181	310	20	Did not fail
3	1502F	3491/17767	310	0.57	Failed
4	297G	8996/4192	280	20	Did not fail
5	1439F	3491/17767	280	0.44	Failed
6	431A	5684/17337	250	20	Did not fail
7	404Zh	2439	250	20	Same
8	915A	5684/17337	250	20	»
*SSO — since the start of operation; ALR — after the last repair.					

quality, the technologist has at his disposal a very limited range of SPD techniques [6]. To have the ability to solve this problem, one of the most suitable is the «soft» method of blade hardening with steel spheres in the magnetic field, allowing increase of welded blade σ_{-1} to the level of solid blades. The proposed method of blade hardening allows performance of differentiated (selective) processing, also with different intensity, of individual sections of blade airfoil [7].

Metallographic examination of the sites of blade fracture after testing was performed. Fracture is of fatigue nature with sites located on the leading edge in the area of the welded joint. Cracks propagated through the weld with transition into the blade base material. Welding defects of the type of inner cavities and micropores were revealed in blade fracture on the face of the leading edge, the size of which does not exceed the admissible requirements for standard welded joints.

Results of metallographic examination of blades with welded fragment revealed that impact of the thermal cycle of welding and heat treatment lead to grain coarsening (Figure 6).

Fracture sites are located on blades at average distance of 4–5 mm from weld axis that coincides with the data obtained in the work on determination of welded sample fracture sites [8].

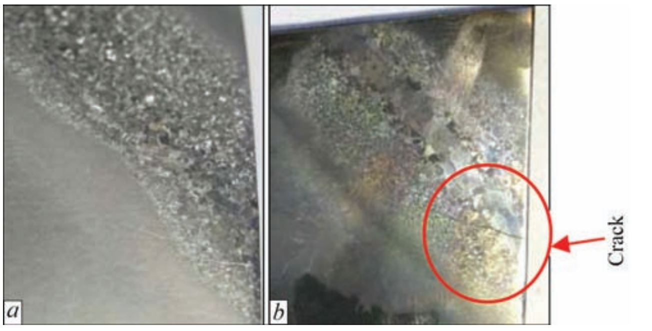

Figure 6. Structural changes after welding: *a* — coarse-grain section; *b* — welded joint fracture

Investigation of the microstructure was performed in Zeiss Axio Observer microscope with 50–500 magnification. View of macro- and microstructure of the weld zone is shown in Figures 7, 8.

Weld material has an acicular structure with coarse grains of primary β-phase (Figures 7, *a*; 8, *a*). In HAZ metal the microstructure is also represented by coarse grains of β-phase, with intragranular lamellar structure with their transition to globular-lamellar form (α + β)-phase of base material (Figures 7, *b–d*; 8, *b–d*). Base metal microstructure corresponds to the second type of microstructure scale No.1 OST 1 90002–86.

Fractures along the opened blade cracks are of a gray hue and partially damaged. Judging by the preserved sections and by macroindications they are of fatigue nature, with sites located at the leading edge at

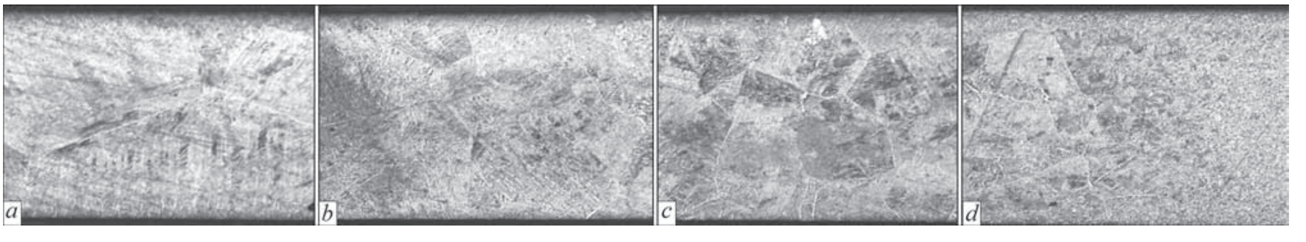

Figure 7. Macrostructure (×50) of blade weld zone: *a* – weld; *b* – weld + HAZ; *c* – HAZ; *d* – HAZ + base metal

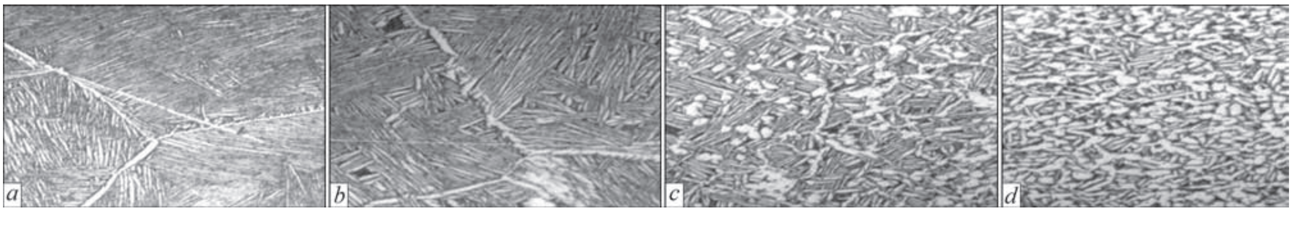

Figure 8. Microstructure (×500) of blade weld zone: *a* — weld; *b* — weld + HAZ; *c* —– HAZ; *d* — base metal

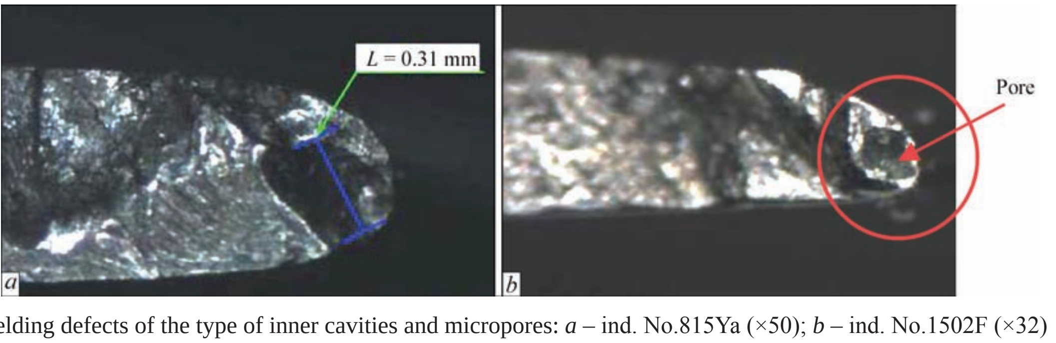

Figure 9. Welding defects of the type of inner cavities and micropores: *a* – ind. No.815Ya (×50); *b* – ind. No.1502F (×32)

the distance of about 70–72 mm from the blade upper end face in the zone of EBW weld with subsequent frontal development from the back to the trough of the blade (Figure 7). Having analyzed the fracture structure, we can see that crack propagation in blades with ind. Nos 1502F and 1439F ran through the weld to the length of 7 and 9 mm, respectively. It is indicated by coarse-grained structure, with subsequent propagation through the base metal with fine-grained structure. In blade No.815Ya crack propagation occurred on the length of 20 mm through the welding zone without reaching the base material, which is indicated by coarse-grained structure of the fracture. It should be added that presence of welding defects of the type of inner cavities and micropores was revealed in the fracture of blades (ind. No.815Ya, ind. No.1502F) on leading edge face, the size of which is admissible for standard welded joints (Figure 9).

Conclusions

1. Results of fatigue tests revealed lowering of σ_{-1} of solid blades, after certain operation time that corresponds to the level of σ_{-1} of welded blades.

2. Blades testing with vibrations by the fourth bending form showed that fracture of both the welded and solid blades occurred in the same manner in the site of the highest stresses, concentrated in the upper part of the airfoil leading edge, and it coincided with part of the trajectory of the fragment weld.

3. Weld trajectory should be located beyond the zone of action of maximum stresses. Here both the fourth and the first bending forms should be taken in to account.

4. Main directions of increasing σ_{-1} of welded blades can be as follows:

• elimination of weld microdefects, revealed at metallographic examination;

• testing a selective method of hardening with metallic spheres in a magnetic field.

4. Considering different operating time and insufficient quantity of data, it is rational to continue performance of work on repair of fan blades with subsequent determination of σ_{-1} of blades, having the same operating time and taken from one D-36 engine.

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