Effect of technological heredity on the fatigue strength in the manufacture of gas turbine engine blades

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Abstract. In the study, the task of researching of the finishing-strengthening machining stage of gas turbine engine compressor blades manufactured of titanium and nickel-chromium alloys in order to extend their service life was solved. The application of electrochemical pulse machining as a technological heredity barrier was substantiated since this method allows a considerable decrease of the residual stress and surface layer work hardening. To ensure the extended service life of blades, the conditions for the subsequent finishing-strengthening machining were identified.

1. Introduction

Modern aircraft engines have a rather complex design and demonstrate a large degree of manufacturing labour-intensity. Strict operating requirements are imposed on them including their operational reliability. Therefore, in serial manufacture of engines, much attention is paid to the issues of reducing labour input and improving the manufacturing quality to enhance the operational reliability and service life of the gas turbine engines while reducing their self-cost. An important feature in the manufacture of engines is the intent of extending service life for serialized products by implementing design and technological methods. Furthermore, the blade is one of the most loaded parts of the gas turbine engine, and, to a large extent, it produces a great impact on the service life and operational reliability of the engine. Therefore, improving the blade service life will reasonably favour extending the engine service life. Basic service life-defining properties of the blade surface layer are developing in the course of the final machining; therefore particular attention is paid to the finishing machining technology applied for the GTE compressor blades.

The shortcoming of the airfoil final machining methods causes necessity of airfoil profile manual correction to ensure the desirable blade geometry. However, the worker’s professional competence (a subjective factor) produces a great impact on the blade surface quality. The occurrence of burn marks on the blade airfoil surface after the correction bench work may be stated to illustrate the unfavourable influence of the subjective factor. The decisive effect on burn makes is produced by the workman’s qualification, labour skills and state, as well as by the applied efforts, which are necessary in grinding. All this causes irregular quality characteristics of the blade airfoil surface layer. Therefore, the decreased scope of manual blade airfoil correction works is favorable both for decreasing of the labour intensity in manufacturing the engines and extending their service life.

With a certain degree of convention, rotor blades may be divided into three standard sizes: large, medium and small. Low pressure compressor (LPC) rotor blades with the airfoil length of 300...500 mm, the blade chord of 100...250 mm may be referred to the large-size blades. They are manufactured
of titanium alloys. The medium-size blades have the airfoil length of 100…200 mm with a chord of 50…80 mm. All the rest are referred to the small-size ones. As a rule, these are high pressure compressor blades with the maximum airfoil length of 15…35 mm and the chord size of 11…30 mm. The most typical of them may be found in modern two- and three-shaft gas turbine engines, where high air compression rates are implemented. Therefore, the last stages of high pressure compressors (HPC) are equipped with blades of the maximum airfoil length of 15 mm and the chord of 11 mm. Since the HPC blades operate at high temperatures, nickel-chromium steels and alloys are applied for their manufacture. The design features of these airfoils are defined by strict roughness requirements for all the path surfaces (R_а=0.32…0.08 µm), the thin profile (C_{max}=1.1 mm) and the maximum radius of the leading and tailing edge being 0.1 mm. Based on the operating conditions of axial compressors, the blades shall comply with the requirements as follows:

- The blade material shall conform to the heat-resistant and hot-temperature stability requirements in the effect of high temperatures, pressure drops and revolutions;
- The weight and sections of blades shall be minimal and their dimensions shall be highly precise thus ensuring the parametrical stability and high compressor efficiency;
- Blade path surfaces shall demonstrate a low roughness indicator, since it helps reducing the losses in a gas flow and increasing the fatigue resistance;
- The labour effort of the technological process shall be kept to a minimum.

Success achieved in the application of low-allowance workpieces raises the topicality of the issue of developing a technology allowing one to process openwork pieces of hard-to-treat materials. It should be noted, that small blades are deprived of the developed base surfaces. In these conditions, circular (airfoil, shroud and edges simultaneously) electrochemical dimensional machining (ECM) of the airfoil profile from the finished root becomes efficient.

However, this is true only for the case, when the ECM is used as a final shaping operation to ensure compliance with the drawing’s requirements. The enhanced ECM precision of the airfoil profile and path surfaces allows abandoning the subsequent manual profile correction.

A special feature of medium-size blades resulting from their operating conditions is that, firstly, they may be manufactured both of titanium and of iron-chromium-nickel alloys. Secondly, smaller dimensions, as compared to the LPC blades, allows using low-allowance workpiece manufacturing methods, e.g. high-velocity forming. Thus, the minimum allowance value along the airfoil will be decreased to 0.3…0.5 mm and its irregularity will be 0.6…1.3 mm. That is, with a minor allowance, its irregularity is rather considerable. The allowance may not be removed in two or three operations, as compared to the LPC blade airfoil. The airfoil machining using edge and abrasive tool is problematic due to the considerable impact and thermal effect produced on the workpiece openwork airfoil. High requirements for the airfoil profile precision and its displacement relative to the root reduce them to small-size blades. All the above-mentioned makes the ECM a priority airfoil machining method which may reliably ensure a non-stressed allowance removal to exclude a considerable impact and thermal effect, caused on an airfoil, and ensure the uniform distribution of minimal surface residual stresses in all the airfoil sections after machining provided the limited dimensions of basing surfaces.

2. Materials and methods

Presently, the ECM is used not only for the airfoil machining, but also in treating of bladed discs; in particular, the work [1] provides the experimental ECM data for the Ti60 titanium alloy which is used in the manufacture of bladed discs for the gas turbine engine compressor. The machining results for interblade areas of the blisk of the given alloy were obtained ensuring high precision of the blade profile (the profile error of 0.05…0.07 mm).

Including the airfoil ECM operation in the rotor blade manufacturing process is expedient since it ensures the smallest level of residual stresses in the airfoil surface layer as compared to other mechanical machining types. In addition, multiple studies have shown that the blades, which have passed the electrochemical machining and the respective strengthening machining, possess the
improved strength properties as compared to those ones which undergone the mechanical machining and the subsequent work hardening. The durability and fatigue strength is improved up to 20%. For example, titanium alloys after the electrochemical machining demonstrate the improved endurance characteristics at an optimal performance level. A defective layer from the preceding machining is removed during the ECM. Furthermore, the removal is not accompanied by the power effect on the surface being treated. Therefore, the electrochemical airfoil dimensional machining represents a special technological barrier of the negative technological heredity (TH).

It should be noted that the analysis of technological machining processes from the TH standpoint has been employed by Minsk, Moscow and Samara technological schools since the 80s, and recently this approach has become widespread in analysing various technologies:

- Metal working;
- Machining of composite materials and intermetallic compounds;
- Volumetric deformation technologies;
- Assembly.

Thus, in work [2] the authors propose studying the manufacturing technology for metal structures as a sequence of macroscopic, microscopic and submicroscopic transformations characteristic of the structure initiation from the TH standpoint to forecast the product quality. As an example of such approach, a method of continuous deformation nanostructuring is employed, allowing the authors to define the evaluation strategy basis for various multi-stage material machining processes to achieve the required set of properties.

The work [3] contains a comparative analysis of TH factors for the parts manufactured both of metal alloys and polymer materials. During the analysis, the factors that have the greatest influence on the heredity of properties were identified. Technological connections ensuring the heredity transfer from one technological operation to the other were considered.

The authors of the work [4] also employed the TH theory in analysing the hydraulic cylinder manufacturing technology; in addition, the mathematical statistic device was involved to estimate the efficiency of production operations. All these allowed the authors to find the most acceptable hydraulic cylinder machining option, ensuring the suppression of negative heredity.

In addition, the researchers [5] analysed the technology for manufacture of a cylindrical gearwheel with involving the TH theory and a multi-factor correlation analysis. As a result, a flow diagram for the machining error heredity in manufacturing the cylindrical gearwheel was developed.

In work [6], an approach from a TH perspective in analysing machine working of casts and the respective assembly of the item jointly with the use of the functional gradient structure model of grain boundaries was employed. This allowed determining the influence of cutting rates on formulating the structural stress raisers during finishing cast milling.

In article [7], following the rough-turning and finish turning example and the subsequent surface plastic deformation, the methods of surface quality control methods for the machine parts and their performance characteristics considering the TH were analysed.

The authors of work [8] employed the TH principle for a comparative analysis of the bearing ring working technologies ensuring the minimal adhesion wear in the subsequent operation.

In article [9], the authors, relying on the TH theory, studied the workpiece hot volumetric deformation process, which allowed them to efficiently suppress the negative heredity, improving the plasticity of high-strength aluminium alloys as well as discovering implementability of phase transitions in manufacturing semi-finished products within thixotropic conditions close to superplastic deformation.

In work [10], the influence of TH on the strength and service life of the welded joint between the header and the heat exchange tube was studied. The residual stresses in the header assembly were determined depending on the main technological pressing parameters and strength characteristics of the tube and header materials.

Within this work, aimed at introducing the airfoil electrochemical pulse dimensional machining into the blade manufacturing technology as a finishing machining method, we have performed
complex studies using the sample blades and actual blades to search for the optimal electrolytes and machining conditions. In addition, the studies included the subsequent strengthening machining and fatigue testing of blades with the airfoil treated under the optimal ECM conditions. Also, tests are mandatory when introducing changes to the existing technological part machining process stipulating the engine service life [11].

This work is a continuation of the authors’ cycle of works on the ECM information modelling [12].

3. The comparative studies of the final stage of the gas turbine compressor blade manufacturing technology

The final stages of manufacturing technologies for the titanium alloy LPC rotary blade and the chromium nickel HPC blade were chosen as the subjects of research. The airfoils of the mentioned blades underwent finishing machining using the electrochemical pulse dimensional machining in electrolytes under conditions ensuring the preset precision parameters. The residual stresses in the airfoil surface layer after the pulse ECM at the optimal performance were below 100-150 MPa, thus demonstrating the negative value with the occurrence depth of less than 100 µm for all the blade materials. In other words, the ECM has produced almost no stress in the surface airfoil layer thus representing a negative technological heredity barrier for the stressed condition of the surface layer.

Further, strengthening machining using different methods was applied to the blades according to the options as represented in table 1.

| Table 1. The options of surface plastic machining of the blade airfoil after the ECM |
|---------------------------------|---------------------------------------------------------------------------------|
| For the rotary blade of the EP718VD alloy | ECM + glass micro-ball strengthening (glass-MB) + vibrogrinding |
| | ECM + glass-MB strengthening |
| | ECM + steel micro-ball strengthening (steel MB) + vibrogrinding |
| For the rotary blade of the VT-8 alloy | ECM + glass-MB strengthening |
| | ECM + glass micro-ball strengthening + vibrogrinding |
| For the guide blade of the EP718VD alloy | ECM (initial option) |
| | ECM + manual polishing |
| | ECM + steel -MB strengthening |

The blades treated according to these blade diagrams underwent the standard fatigue testing with a basic number of loading cycles being \( N \cdot 10^6 \).

The experimental data obtained were subjected to the linear regressive analysis resulting in determination of the fatigue strength and stress-cycle relationship values for the failure probability, \( P=50\% \).

The analysis results are given in figure 1.

The dispersion analysis determined the statistical significance of the technological factors’ influence according to the strengthening options adopted in the manufacturing process. As a result of the unifactor dispersion analysis, it was established that the testing results of the working blades manufactured of the EP718VD alloy treated with ECM + micro-ball strengthening, both with the vibrogrounding and without it, belongs to the same universe general population and may be considered as a consolidated option.

The selection of hardening bodies (glass and steel micro-balls) is a considerable factor, therefore the results of testing HPC blades of the EP718VD with the ECM machining + steel micro-ball strengthening + vibrogrinding form a separate population. It was also established that the testing results of blades manufactured using the ECM method and steel micro-ball strengthening with the preliminary airfoil polishing and without polishing shall belong to the same general population and
may be considered as a joint option.

![Stress-cycle curve images](image)

**Figure 1.** The stress-cycle curve of the HPC rotary blades manufactured of the EP718VD alloy after:
(a) ECM + steel micro-ball strengthening + vibrogrinding;
(b) 1 – ECM + glass micro-ball strengthening + vibrogrinding; 2 – ECM + glass micro-ball strengthening;
(c) 1 – ECM + glass micro-ball strengthening + vibrogrinding; 2 – ECM + glass micro-ball strengthening;
(d) ECM;
(e) ECM + manual polishing;
(f) 1 – ECM + steel micro-ball strengthening; 2 – ECM + manual polishing + steel micro-ball strengthening.

The dispersion analysis of testing results for blades forming options without micro-ball strengthening using manual polishing and without it has demonstrated that the testing results for these
two options belong to different populations.

The dispersion analysis of other combinations of options was meaningless due to the obvious difference of testing results. The linear regressive analysis was repeatedly performed for the generalized options. Therefore, following the results of strength testing, the following values of fatigue strength were obtained, which are given in table 2.

Previous studies for the EP718VD blades, which airfoils were treated by the double milling and the subsequent manual polishing as well as subjected to steel microball strengthening and vibrogrinding, demonstrated in the fatigue testing that their fatigue resistance value was lower and amounted to \( \sigma_{\text{f}} = 512 \) MPa. For the glass microball strengthening option, it is \( \sigma_{\text{f}} = 470 \) MPa. This means a considerable increase of the fatigue strength for the blades treated by ECM with the subsequent strengthening machining.

For airfoils which failed during the strength testing, metallographic studies were carried out which confirmed the correspondence to the metal quality specifications. The condition analysis of the blade surfaces was performed with a MBS-2 binocular microscope with the magnification of 12.5 and x25.

The surface of blades of EP718VD alloy option 1 is grey, matte, demonstrating particular traces of knocking with glass micro-balls and their slipping. The option 2 blade surface is light grey, matte, demonstrating traces of glass micro-ball machining. The option 3 blade surface is grey, matte, demonstrating traces of knocking with glass micro-balls and their slipping.

| Table 2. The values of fatigue strength \( \sigma_{\text{f}} \), MPa after the strength tests performed |
|-----------------------------------------------|
| Working blade of the EP718VD alloy             |
| ECM + glass micro-ball strengthening (with/without vibrogrinding) | 540 |
| ECM + steel micro-ball strengthening + vibrogrinding | 580 |
| 4th stage rotary blade of the VT9 alloy        |
| ECM + glass micro-ball strengthening (with/without vibrogrinding) | 370 |
| 6th stage guiding blade of the EP718VD alloy   |
| ECM                                           | 280 |
| ECM + manual polishing                         | 360 |
| ECM + steel micro-ball strengthening (with/without preliminary polishing) | 480 |

The microanalysis performed in fractional blade sections established that the structure of blade material is normal for the EP718VD alloy solid solution + strengthening phases. The grain size for all the blades corresponds to points 5-6 of the grain scale under GOST 5639-82 and complies with the requirements of technical specifications for blades. To determine the blade surface strengthening level for all the options, the micro-hardness was checked using the PTM-3 device with the load of 50 g. The micro-hardness measurement results are given in table 3. The micro-hardness measurement results demonstrate that the increase of surface micro-hardness corresponds to the work hardening level 31 (39%).

As a result of the research, an optimal technology for the finishing-strengthening stage of the HPC blade airfoil treatment after pulse ECM was offered. The employment of this technology decreases the influence of negative technological heredity on the type II size precision. It enables us to form the optimal surface layer quality.

| Table 3. The measurement results of micro-hardness after different machining methods |
|-----------------------------------------------|
| Working blade of the EP718VD alloy             |
| ECM + glass micro-ball strengthening (with/without vibrogrinding) | 540 |
| ECM + steel micro-ball strengthening + vibrogrinding | 580 |
| 4th stage rotary blade of the VT9 alloy        |
| ECM + glass micro-ball strengthening (with/without vibrogrinding) | 370 |
| 6th stage guiding blade of the EP718VD alloy   |
| ECM                                           | 280 |
| ECM + manual polishing                         | 360 |
| ECM + steel micro-ball strengthening (with/without preliminary polishing) | 480 |
Furthermore, the improved fatigue resistance is ensured with retaining the increased long-term strength as in case of general pulse ECM. After electrochemical machining, the residual stresses are minimal in the surface layer, the work hardening is absent.

4. Conclusion
Therefore, in testing various blade airfoil machining options, it was demonstrated that the electrochemical pulse dimensional machining is the best method to comply with the requirements for the finite machining technique with the subsequent micro-ball strengthening, representing the barrier for the negative technological heredity. In this event, a considerable growth of long-term strength (approximately 10-15%) is ensured as compared to the traditional mechanical working of the airfoil and the consequent strengthening, which is greatly in line with the results of studies performed earlier for the medium- and large-sized blades.

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