Results of Investigative Tests of Gas Turbine Engine Compressor Blades Obtained by Electrochemical Machining

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Abstract. The paper highlights results of the investigative tests of GTE compressor Ti-alloy blades obtained by the method of electrochemical machining with oscillating tool-electrodes, carried out in order to define the optimal parameters of the ECM process providing attainment of specified blade quality parameters given in the design documentation, while providing maximal performance. The new technological methods suggested based on the results of the tests; in particular application of vibrating tool-electrodes and employment of locating elements made of high-strength materials, significantly extend the capabilities of this method.

Introduction

Electrochemical machining is a unique technological method that allows obtaining geometrically complex, shaped surfaces on the products made of materials hard-to-machine by traditional methods. This explains the increasing spreading of ECM as the primary method of profile sizing of compressor blade airfoils of modern gas turbine engines.

However, in addition to wide technological capabilities, the ECM differs from other machining methods through complexity of the main and auxiliary equipment, complexity and high cost of the accessories used (for blade locating and fastening), high energy intensity of processes, hazardous working conditions for personnel and negative impact on the environment.

ECM accuracy is determined by a combination of factors, the main of which are as follows: value of the interelectrode gap and accuracy of its adjustment, localizing capability of electrolyte, its type, concentration and pumping conditions; as well as manufacturing accuracy and correction of the tool-electrode; electrical machining modes; accuracy of the equipment used; electric potential uniformity.

Advanced method to improve ECM accuracy

One of the methods to improve machining accuracy is electrochemical machining with tool-electrode vibration, which is characterized by electrode harmonic oscillations and pulse current pile-up synchronized with them (oscillating electrodes).

For electrochemical machining of gas turbine engine blades, besides the kinematic diagram with electrode vibration, the pulse cyclic and continuous tool-electrode feed diagrams are applied (Table 1).
Table 1 Comparison of kinematic diagrams applied at electrochemical machining of GTE blades

| Comparison criterion                                      | Kinematic diagram |
|----------------------------------------------------------|-------------------|
| Tolerance extremes of blade airfoil dimensions, mm       | ± 0.08            |
|                                                           | ± 0.02            |
|                                                           | ± 0.1             |
| Performance rate, mm/min                                 | 0.4               |
|                                                           | 0.2               |
|                                                           | 0.5 – 0.8         |
| Possibility to take into account irregularities of       | +                 |
| distribution of allowance and blade deformations in the  | +                 |
| course of machining                                      | –                 |

Table 1 demonstrates that the kinematic diagram with electrode vibration provides higher machining accuracy combined with lower performance. Therefore, the kinematic diagram with electrode vibration is the most applicable for blade manufacture with high accuracy and a wide twist angle (Figure 1). However, in order to reduce machining time it is necessary to minimize the value of the allowance removed.

Figure 1. Exterior view of the blade manufactured with application of the kinematic diagram with electrode vibration

Results of compressor blade tests

Tests in electrochemical machining of blades with oscillating tool-electrodes were carried out in two stages. At the first stage, the optimal modes of electrochemical machining with oscillating tool-electrodes were defined. The second stage implied the study of geometrical parameters and roughness of the blade airfoil profile in dependence on the obtained values of machining modes.

Research in order to define ECM modes was conducted on the second stage compressor guide blade (Figure 1) made of TA6V titanium alloy (Table 3) in accordance with the operational definition drawing for machining of airfoil elements at the operation of electrochemical machining (Figure 2) with subsequent inspection of blade airfoil profile geometrical parameters according to Table 2.
Figure 2. Operational definition drawing of the second stage compressor guide blade airfoil machining

Table 2 Geometrical parameters of airfoil profile of blade semi-products after ECM

| Indicator name                                           | Section | 00  | 10  | 20  | 30  | 50  | 70  | 80  | 90  |
|----------------------------------------------------------|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Maximal airfoil profile thickness, mm                    | Rated value | 0.966 | 1.023 | 1.084 | 1.107 | 1.399 | 1.930 | 2.256 | 2.483 |
| Tolerance extremes                                       | +0.15  | -0.05 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 |
| Leading blade edge thickness, mm                         | Rated value | 0.717 | 0.752 | 0.786 | 0.813 | 0.960 | 1.268 | 1.462 | 1.603 |
| Tolerance extremes                                       | +0.15  | -0.05 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 |
| Trailing blade edge thickness, mm                        | Rated value | 0.455 | 0.446 | 0.453 | 0.442 | 0.539 | 0.588 | 0.580 | 0.637 |
| Tolerance extremes                                       | +0.15  | -0.05 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 | +0.15 |
| Airfoil profile roughness, $Ra$, µm                      | Rated value | 3.2   |       |       |       |       |       |       |       |
| Tolerance extremes                                       | ±1     |       |       |       |       |       |       |       |       |

Table 3 Chemical composition of TA6V alloy

| Element | Sign | Percentage of total |
|---------|------|---------------------|
| Titanium | Ti   | 88.37 – 90.62       |
| Aluminum | Al   | 5.5 – 6.75          |
| Vanadium | V    | 3.5 – 4.5           |
| Carbon   | C    | 0.08                |
| Iron     | Fe   | 0.3                 |

Specifics of electrochemical etching of titanium alloys considerably complicate implementation of GTE blade airfoil profile machining operation. It is due to the oxide film growth on the part surface, right up to attainment of electric potential of a certain breakdown value, sufficient to break the oxide film and to implement the process of removal of material main allowance. Increase of ECM process efficiency for blades made of titanium alloys can be achieved by means of machine setting.
To define recommended machining modes the research was carried out within the ranges of ECM mode parameters specified in the professional literature [5, Tables 4.3, p. 183] (Table 4).

Table 4 The range of parameters ECM

| Process parameters ECM |
|------------------------|
| **Electrical** |
| Type of current | Direct current |
| Voltage | 5 – 30 V (Constant or a pulse) |
| Current | 50 – 40 000 A |
| Current density | 10 – 500 A/cm² |
| **Electrolyte** |
| The type and concentration |
| Most commonly used | NaCl (60 – 240 г/l) |
| Frequently used | NaNO₃ (120 – 480 г/l) |
| Temperature | 20 – 50 °C |
| Consumption electrolyte | 1 l/min/100A |
| The speed of the electrolyte | 1500 – 3000 m/min |
| The pressure at the inlet of the electrolyte | 0.15 – 3 MPa |
| The outlet pressure of the electrolyte | 0.1 – 0.3 MPa |
| **Electrode** |
| Electrode gap | 0.05 – 0.3 mm |
| Feed rate electrode | 0.1 – 20 мм/мин |
| **ECM** |
| Accuracy of machining |
| two-dimensional surfaces | 0.05 – 0.2 mm (0.02 – 0.05 during pulse ECM) |
| three-dimensional surfaces | 0.1 mm (0.05 during pulse ECM) |
| Surface roughness | Ra = 0.1 – 2.5 μm |
| Processing performance | 1200 – 2500 mm³ per 1000 Amps |

The first stage of tests implied experimental works in definition of the change range of the most critical parameters of the process and the degree of their impact on the part characteristics, such as electric parameters (voltage, pulse duration, pulse trailing edge phase, form); electrolyte pressure; and vibration cycle.

The aim of this stage was achievement of the maximal performance of the process while providing its stability, reiteration of results, at that the blade quality indexes (maximal airfoil profile thickness, edge thickness, roughness value etc.) had to be as close to the requirements of design documentation as possible. Analysis of design of equipment and tools was carried out also in order to identify possiblities of their further improvement.

The second stage implied ECM modes on the plant with oscillating electrodes based on the group of investigative tests subject to the above-mentioned boundary conditions and capabilities of the equipment used.

As varying parameters of ECM modes, the following ones are used:
1. Vibration cycle (T).
2. Pulse voltage (U).
3. Pulse duration ($t_i$).
4. Pulse trailing edge phase ($\alpha$).

As a result of implementation of the first stage of research, a control program was developed for the experimental plant allowing carrying out Ti-alloy blade electrochemical machining in automatic mode.

The aim of the second stage of the work was research of blade geometrical parameters and specification of the process parameters which values were obtained at the first stage.

Based on the analysis of the data obtained for electrochemical machining of blades made of titanium alloy at the experimental plant with oscillating electrodes the following process parameters were obtained (Table 5).

### Table 5: Process parameters of electrochemical machining with electrode oscillation

| Name of the parameter                    | Measuring unit | Value     |
|------------------------------------------|----------------|-----------|
| **Parameters of the main allowance removal** |               |           |
| Vibration cycle                          | microsecond    | 27 – 33   |
| Electrolyte pressure                     | atm            | 1.5       |
| Rinse cycle time                         | second         | 10        |
| Number of rinse cycles between sensing   |                | 1         |
| Rinse time                               | second         | 0         |
| Rinse gap in relation to the machining gap | µm             | 0         |
| Difference of allowances to include aligning | mm             | 0.1       |
| Machining gap                            | µm             | 70        |
| Initial feed rate                        | mm/min         | 0.1       |
| Pulse voltage                            | V              | 19        |
| Pulse form                               | –              | Bcos      |
| Pulse duration                           | ms             | 10        |
| Phase of the pulse trailing edge         | degree         | 240       |
| **Parameters of allowance aligning**     |               |           |
| Machining gap                            | µm             | 70        |
| Initial feed rate                        | mm/min         | 0         |
| Pulse voltage                            | V              | 15        |
| Pulse form                               | –              | Bcos      |
| Pulse duration                           | ms             | 4         |
| Phase of the pulse trailing edge         | degree         | 120       |

**Technological methods to increase ECM quality**

GTE compressor blade test results showed that the topical issue hindering improvement of GTE compressor blade ECM process is poor accuracy and, above all, fragility of the equipment used.

As a rule in the process of machining, machine-retaining devices applied during ECM of blade airfoil are located inside the machining cell (plant) and are fully immersed in the electrolyte. In addition to the mechanical impact on the elements of the device, physics of the ECM process causes combined corrosion and electrochemical effects on the device. To the greatest extent the locating elements are damaged immediately contacting the blade work-piece under machining. On the locating elements, centers and prisms, holes and caverns are formed (Figure 3) resulting in rapid loss of machining accuracy, need for replacement and downtime of expensive equipment.
It is obvious that provision of the lifetime for locating elements of blades in this case is possible only at the expense of selection of the used construction material and, to some extent, by improving design and technology of manufacture of locating elements.

The problem of material selection for manufacture of blade locating elements consists in the need to provide simultaneously chemical resistance, absence of deformations and mechanical damages of locating elements. In addition, much attention is paid to reducing the cost of manufacture and operation of devices, directly affecting the prime cost of products (blades and the engine in general).

Now for the manufacture of locating elements mainly niobium is used having high chemical resistance. The disadvantages of niobium are low mechanical properties (particularly hardness), some difficulties in machining and extremely high cost of the material.

Thus, it is necessary to find the material to replace niobium with comparable chemical stability, high mechanical properties, acceptable machinability indexes and lower cost.

It should be noted that as electrolytes in electrochemical machining the aqueous solutions of neutral salts are used possessing high corrosion activity in relation to vulnerable parts of technological equipment and tooling devices, including locating elements.

The equipment and devices used for locating and fixing the blades can be of different design, however, regardless of the layout of devices there are three main locating elements in their composition being in direct contact with the machined blade: the basic center, the retaining center and the prism.

The locating elements are exposed to the greatest damage during the blade ECM process due to the electrochemical, corrosion and mechanical impact. As practice shows, the most common damages and defects of the device locating elements for blade ECM are the following ones:

- linear wear and crushing of working surfaces,
- etching of working surfaces with formation of holes,
- cracking and material spalling of the locating elements.

As a rule, cracking and spalling set a limit to the possibility to mount the work-piece in the device requiring immediate replacement of locating elements. Crushing and etching of locating reference points results in displacement of the work-piece in relation to the reference target position, in locating error. For the etching is inhomogeneous, as a rule, it results in a twist of the blade relative to the prism (Figure 4), or in a turn relative to the center line (Figure 5). In a number of cases, geometrical summation of these errors can be observed.
At present in modern enterprises of aircraft engine building branch to produce locating elements niobium BH-3 GOST 16100-79 [2] is applied, which resistance to anodic attack is provided at the expense of formation of the passive oxide film (Nb2O5) under conditions of impact of a corrosive medium (concentrated aqueous solutions of neutral salts). However, this material is rather plastic, which has negative impact both on its serviceability (crushing), and on cutting ability (build-up forming on the tool face, "blunting" of abrasion wheels. Hardness of niobium is 75 HB, which is considerably lower than hardness of the material applied to GTE blade manufacture (270-360 HB). Low hardness of locating elements results in a number of cases in their damage (crushing) by fixing forces, which leads to the need of their periodic diagnostics, replacement and set-up of equipment. Low hardness of this material and its high price lead to rise in cost of ECM process implementation. In addition, it should be noted, that application of special equipment to produce attachment elements of niobium is not needed. Existing multipurpose equipment suffices. The technological process of production of locating elements includes operations of turning and grinding. It is obvious that niobium does not completely meet specifications for materials of locating elements formulated above. However, due to its properties, in particular susceptibility of a protective oxide film, niobium came into widespread acceptance at manufacture of devices for ECM in the absence of alternatives.

The analysis of literature sources [3-6] allowed singling out three main trends in search of optimal materials to produce locating elements in ECM operations:
1. Materials of high hardness (ceramics, leucosapphires).
Hot-pressed nitride ceramics chosen as potential material for manufacture of locating elements is a mixture of aluminum oxide Al₂O₃ and titanium nitride TiN. The main advantages of this material are:
- low electrical conductivity which results in higher resistance to chemical and electrochemical dissolution;
- high hardness (>400 HB), which considerably exceeds hardness of work-pieces of the GTE blades manufactured, which determines absence of deformations and low wear of elements in the process of device operation;
- sufficient workability (ceramics allow obtaining locating elements by hot-pressing original powder blends with subsequent grinding of work-pieces until obtaining drawing dimensions).

Leucosapphire presents a sort of ceramics possessing, among other things, maximal hardness characteristics at shock loading. The main disadvantage of this material is low coefficient of cutting ability. The main method to obtain parts of sapphire is multistep grinding distinguishing by low performance. Reduction of labor intensiveness is possible due to extension of tolerances for locating elements by a factor of 1.2-1.5. However, this will result in need to adjust grommets and housings for locating elements immediately as to the element manufactured. Cost of manufacture of work-pieces and that of subsequent machining of leucosapphires, as well as necessity of the following in-place adjustment of other device elements makes its application unreasonable.

2. Plastic and its derivatives (engineering plastics).

Engineering plastics are polymeric materials used for manufacture of machine parts exposed to impact of aggressive media, in particular, concentrated salt solutions (fixture elements, base members, slides, bearing sleeves etc.). The main features of engineering plastics are chemical resistance and inertness, hydrophobic behavior (determining ease of cleaning from electrolyte), high technological effectiveness, low cost of material. To manufacture locating element prototypes plastic Victrex 450 GL 30 was chosen. Preliminary tests demonstrated intolerable value of crushing of locating elements made of plastics, which can be explained through its low hardness.

3. Obtaining hard oxide films on locating elements made of metallic materials (titanium alloys).

Locating elements made directly of titanium alloys show certain resistance to etching, however a considerably lower one than that needed for blade batch manufacture.

Indisputable advantage of this material is availability, including possibility to use titanium wastage formed when producing aircraft engines, as well as high mechanical properties.

To protect surfaces of locating elements efforts were undertaken to obtain intentionally oxide films on titanium alloys BT3, BT9, BT20, and BT22. Practical data showed the fact of formation of the most stable and damage-resistant oxide films on titanium alloy BT3.

Based on results of the analysis, comparative tests to determine the selective material for manufacture of blade locating elements in operations of ECM were carried out for three materials:
- niobium (applied at present);
- nitride ceramics (Al₂O₃ + TiN);
- oxidized titanium BT3.

The tests aimed at inspection of serviceability of the materials chosen as locating elements and elimination of materials with low resistance. During tests, the blades were manufactured until occurrence of limiting state (non-serviceability) of locating elements. Tests were conducted for three sets of locating elements, after that the determined indexes of resistance were averaged.

The highest indexes of resistance were achieved for the elements made of oxidized titanium alloy BT3 (aged during 12 hours in temperature 700 – 800°C). Thus, the optimal material for manufacture of blade locating elements in the operation of airfoil ECM is oxidized titanium alloy BT3.

**Conclusion**

As a result of the investigative tests on the electrochemical machining of blades with oscillating tool-electrodes the features of this process were considered, the optimum process parameters of electrochemical machining of blades made of titanium alloys, ensuring the achievement of quality...
parameters of the blade specified in the design documentation, while providing maximum performance.

The technological methods under consideration, in particular use of vibrating tool-electrodes and use of locating elements made of high-strength materials can significantly extend the capabilities of this method.

References
[1] Yu S Eliseyev, V V Krymov, A A Mitrofanov, B P Saushkin Physicochemical machining methods in GTE production under the editorship M Drofa (2002) 655
[2] Lifshits, A. L., Kravets A. T., Rogachev I. S. et al. Metal electro pulse machining under the editorship of A. L. Lifshits. – SPB: Let Me Print, 2013 – 156 p
[3] V F Orlov, B I Chugunov Electrochemical shaping M Machinostroyeniye (1990) 240
[4] Yu S Eliseyev, V V Krymov, A G Boitsov Technology of manufacture of aircraft gas turbine engines M Machinostroyeniye (2003) 512
[5] V F Bezyazychny, V A Poletaev, T D Kozhina, V F Bezyazychny, V N Krylov Automation of aircraft gas turbine engine production process M Machinostroyeniye (2012) 560
[6] V A Poletaev Gas turbine engine blade automated manufacturing technology M Machinostroyeniye (2006) 256 p
[7] V G Smirnov Design of technology of final electrochemical machining of gas turbine engine blades in terms of technological heredity (2007)
[8] A R Khamsina Perfecting of technology of GTE part electrochemical machining to improve quality of surface layer and resistance to high-temperature gas corrosion (2010)
[9] E V Smolentsev, Design of electrical and combined machining methods M Machinostroyeniye (2005) 511
[10] Modern electrochemical technologies collected works on the proceedings of All-Russian conference SSTU (2002) 248
[11] T D Kozhina, A V Kurochkin Features of research trials in electrochemical machining with oscillating electrodes 1 (2015) 89-93
[12] T D Kozhina, A V Kurochkin Selection of materials for manufacture of locating elements for GTE compressor blades ECM procedure in order to maintain their manufacture rohrematik cycle 4 (2014) 75-79