7.Gnusarev N.V. Geodezicheskoe i balisticheskoe obespechenie kosmicheskih sistem distansionnogo zondirovania Zemli: uchebnoe posobie. – SPb.: VKA im. A.F. Mojaiskogo, 2008. – 220 s.

8. Moiseev V.S. Applied theory of control of unmanned aerial vehicles: Monograph. – Kazan: GBU "Republican Center for monitoring the quality of Education", 2013. – 768 p.

9. Urlichich Yu.M., Selin V.A., Emelyanov K.S. About the priorities of practical implementation of the development of the space system of remote development of the Earth // Aerospace Courier. – 2011. – № 6 (78). – Pp. 12-19.

DOI 10.53364/24138614_2022_26_3_14
УДК 629.7.036:539.4

[1]**Сайдахмедов Р.Х.**, д.т.н. профессор, [2]**Саидахмедова Г.Р.,** магистр
[1,2]Ташкентский государственный транспортный университет, г. Ташкент, УР.

[1]*E-mail: ravshansaid@mail.ru*
[2]*E-mail: gulyasaid.97@mail.ru*

АНАЛИЗ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ЛОПАТОК ТУРБИН ГТД С ТЕРМОБАРЬЕРНЫМИ ПОКРЫТИЯМИ

ТЕРМОБАРЬЕР ЖАБЫНЫ БАР ГАЗТУРБИНАЛЫҚ ТУРБИНА ҚАЛАҚТАРЫНЫҢ КЕРНЕУЛІ-ДЕФОРМАЦИЯЛАНҒАН ЖАЙ-КҮЙІН ТАЛДАУ

ANALYSIS OF THE STRESS-STRAIN STATE OF GAS TURBINE BLADES WITH THERMAL BARRIER COATINGS

Аннотация. Диагностика реального состояния и остаточного ресурса элементов конструкции авиационного газотурбинного двигателя является главной задачей в рамках решения проблемы обеспечения безопасности при эксплуатации летательных аппаратов.

Важнейшее звено в оценке ресурса и прочности является турбина ГТД - определение напряженно-деформированного состояния (НДС) элементов конструкций, отличающихся сложностью формы и большим количеством зон концентраций напряжений. При этом определение действительных значений деформаций и напряжений и их изменений во времени в процессе эксплуатации требуется как для оценки прочности и ресурса, так и для разработки рекомендаций по оптимизации рабочих режимов и совершенствованию конструкций.

Ключевые слова: напряженно-деформированное состояние, диагностика, жаростойкие покрытия, лопатки турбин ГТД, моделирование.

Аңдатпа. ӘК газтурбиналық қозғалтқышының құрылымдық элементтерінің нақты күйі мен қалдық қызмет ету мерзімін диагностикалау әуе кемелерін пайдалану кезінде қауіпсіздікті қамтамасыз ету мәселесін шешудегі негізгі міндет болып табылады.

Ресурс пен беріктікті бағалаудың ең маңызды буыны GTE турбинасы болып табылады - пішіннің күрделілігімен және кернеулердің шоғырлану аймақтарының көптігімен ерекшеленетін құрылымдық элементтердің кернеулі-деформациялық күйін (СЖС) анықтау. Бұл ретте деформациялар мен кернеулердің нақты мәндерін және олардың жұмыс кезінде уақыт бойынша өзгеруін анықтау беріктік пен қызмет ету мерзімін бағалау үшін де, жұмыс режимдерін оңтайландыру және құрылымдарды жақсарту бойынша ұсыныстар әзірлеу үшін де қажет.

Түйін сөздер: кернеу-деформация күйі, диагностика, ыстыққа төзімді жабындар, GTE турбиналық қалақтары, модельдеу.

Abstract. Diagnostics of the real state and residual life of structural elements of an aircraft gas turbine engine is the main task in solving the problem of ensuring safety in the operation of aircraft.

The most important link in the assessment of the resource and strength is the GTE turbine - the determination of the stress-strain state (SSS) of structural elements that are distinguished by the complexity of the shape and a large number of stress concentration zones. At the same time, the determination of the actual values of strains and stresses and their changes over time during operation is required both for assessing strength and service life, and for developing recommendations for optimizing operating modes and improving structures.

Key words: stress-strain state, diagnostics, heat-resistant coatings, GTE turbine blades, modeling.

An aircraft gas turbine engine (GTE) is a complex technical object. Checking the serviceability, operability and correct functioning - diagnostics of an aviation gas turbine engine is necessary during the operation of the latter to ensure flight safety. Quick identification of malfunctions in complex GTE systems is also necessary to reduce the downtime of the aircraft, which increases its efficiency.

Due to the thermomechanical effect on the structural elements of the gas turbine engine, in particular on the compressor and turbine blades, a geometric change in the airfoil of a rotor or stator blade and a structural change in the blade metals are possible. The relatively small loss of geometry during operation significantly reduces the efficiency of the gas turbine engine as a whole. Prolonged operation in difficult conditions can lead to almost complete replacement of the blades of most compressor and turbine stages.

Operational destruction of parts and assemblies of an aircraft gas turbine engine is caused, as a rule, by the influence of a large number of simultaneously acting factors. Therefore, when designing parts and assemblies of an aircraft gas turbine engine, one of the main conditions for preventing their destruction before the end of the assigned resource is the maximum possible accounting for them, the need for diagnosis. The technical condition of an aircraft engine and aircraft equipment in general depends on the correct choice and accuracy of diagnostics. Therefore, the choice of a method for diagnosing and modeling aviation GTE systems is relevant. Practical application of scientifically grounded methods and means of diagnosing aviation equipment ensures a reduction in its downtime, and a decrease in the cost of funds and labor for maintenance [1].

The introduction of modern aircraft diagnostics methods into the maintenance and repair processes gives a significant economic effect, which is formed as a result of the optimal management of the technical condition of the operating fleet of aircraft. Aircraft diagnostics have a significant impact on flight safety in all maintenance and repair strategies.

At the same time, paramount importance is given to the problem of increasing the reliability and durability of aircraft gas turbine engines, which are inextricably linked with the quality of parts, since almost all performance indicators of products are determined by geometric parameters, physical and mechanical properties of working surfaces.

There are several types of diagnostics for aircraft gas turbine engines. One of the modern methods for diagnosing aircraft engines is the laser method. The laser method is based on obtaining information based on experiment. In works [11,12] modern diagnostics of gas turbine engines by the phase-chronometric method, vibroacoustic control of the technical condition are considered.

There is no other part in technology that works in such difficult and critical conditions as the blades of gas turbines of turbojet engines (Figure 1).

For the manufacture of turbine blades, expensive equipment and rare metals with equally rare physical properties are used. One of the most knowledge-intensive and difficult-to-manufacture components for gas turbine engines is the turbine blade. Products of this precision and level are produced only by six countries in the world, because it requires the most complex design calculations and very high manufacturing accuracy. In addition to Russia, only the US firms (Pratt & Whitney, General Electric, Honeywell), England (Rolls-Royce) and France (Snecma) own the technologies of the full cycle of creating modern turbojet engines.

The reliability of the GTE is significantly influenced by the turbine, the main element of which is the blades. The practical increase in the reliability of the GTE turbine is associated with an increase in the durability of the blades. The task of increasing the reliability of the operation of aircraft gas turbine engines, and in particular of turbine blades, is solved by constructive, technological and operational methods. If the first two tasks are associated with the design of blades, the use of modern materials, in particular, materials obtained on the basis of nanotechnology and technological processes for obtaining parts of gas turbine engines, and operational methods of increasing reliability are associated with the creation of a reliable and effective system for diagnosing aviation gas turbine engines.

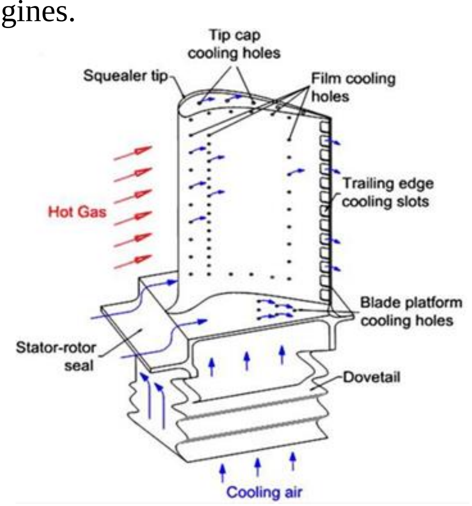

Figure 1 – GTE blades with a cooling system.

One of the main factors that significantly affect the efficiency of the process of diagnosing an aviation GTE is the development of a mathematical model of the process of functioning of the system and diagnostic algorithms. The efficiency of diagnostic processes is determined not only by the number of developed algorithms, but to a large extent by the quality of diagnostic tools, as well as by the development of an adequate multi-parameter model of the system.

An aviation GTE is a complex technical multi-parameter system, and the development of an adequate diagnostic method is an urgent task. One of these parameters of a gas turbine engine is the gas temperature in front of the turbine. During engine operation, the temperature inside the turbine is incredibly high and the higher the temperature of the gas in front of the turbine (T_g), the more powerful and economical the engine works.

Figure 2 shows the evolution of the change in gas temperature in front of the turbine since 1965. The power of the gas turbine engine is associated with an increase in the gas temperature in front of the turbine. Therefore, the developers are constantly improving the materials of the turbine blades and its design. High temperatures and cyclic loads acting on turbine blades create high residual stresses.

Diagnostics of the real state and residual life of the structural elements of an aircraft gas turbine engine is the main task in solving the problem of ensuring safety during the operation of aircraft.

The most important link in assessing the resource and strength is the turbine of a gas turbine engine - the determination of the stress-strain state (SSS) of structural elements that differ in the complexity of the shape and a large number of stress concentration zones. At the same time, the determination of the actual values of deformations and stresses and their changes over time during operation is required both for assessing strength and resource, and for developing recommendations for optimizing operating modes and improving structures.

The stress-strain state of GTE blades can be caused by various types of thermal, bending, centrifugal and vibration loads. The fact is that under conditions of a given thermomechanical loading, some sections of the lining can creep; the resulting residual stresses at low temperatures can cause plastic deformations. For these reasons, during engine operation, material behavior is unlikely to be non-linear, and simulation results are time consuming [10].

To calculate and determine the deformation state, you can use programs such as ANSYS, which allows you to get stress values along the periphery of the blades. This type of approach will simplify blade maintenance and design, and requires experimental data on the properties of the materials used.

One such experimental work in the ANSYS program using finite element analysis (FEM), the kinetics of the stress-strain state of a nickel-based single-crystal (SX) turbine blade is shown [13]

For reducing the loads and increase the reliability and durability of turbine blades in modern aircraft engines, heat-shielding coatings are used.

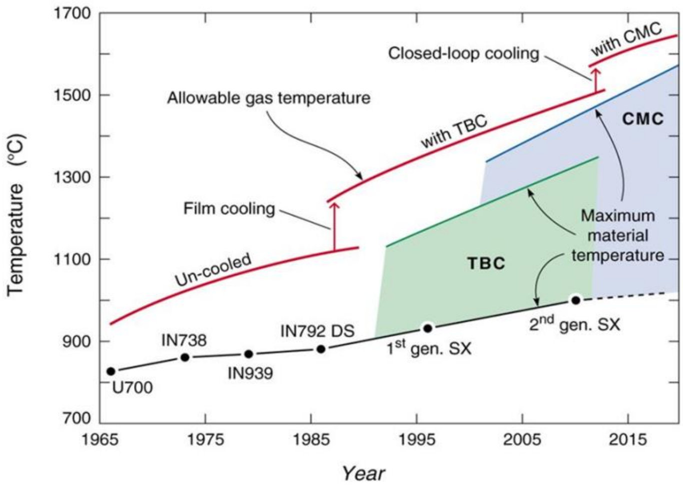

Figure 2 – Evolution of the change in gas temperature in front of the turbine depending on the blade material, thermal barrier coating and cooling.

The heat-shielding coating (TSP), which protects the alloys from high-temperature exposure in an aggressive environment, has a great influence on the durability of operation of GTE blades under thermal cyclic loads (Figure 3).

GTE blades operate under extreme conditions (large temperature differences, erosive wear, corrosion, etc.), ceramic heat-shielding coatings are used to protect them. Unlike heat-resistant coatings, heat-protective coatings protect not only the surface of the blades from high-temperature corrosion, but also the blade material from softening as a result of exposure to high temperatures. A typical structure of the RCP for rotor blades is given in [7].

The role of the surface, stress-strain state and its influence on the performance properties of GTE parts were studied in [3]. The relationship of the surface layer with the operational properties of parts is shown in Figure 4.

During the manufacture and operation of a part, irregularities appear on its surface in the metal layer adjacent to it, the structure, phase and chemical composition change. Residual stresses arise in the part.

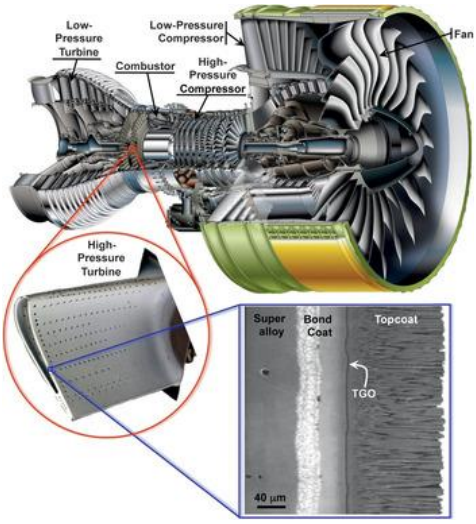

Figure 3 – Main elements of a gas turbine engine and a turbine rotor blade with heat-shielding coatings.

Irregularities on the surface of a part, structure, phase and chemical composition of the surface layer affect its physicochemical and operational properties.

The surface layer has a significant impact on the reliability of the part, assembly and machine as a whole. During operation, the surface layer of the part is exposed to the strongest physical and chemical effects. Failure of a part in most cases starts from the surface (for example, fatigue crack development, wear, erosion, and corrosion).

And this is no coincidence. On the one hand, engine parts are made "openwork", hollow and thin-walled - this is due to the need to reduce weight. On the other hand, GTE parts operate in conditions of high and rapidly changing temperatures, corrosive environments; at the same time, the material of the parts is subject to high static and dynamic stresses, the amplitude and frequency of which vary over a wide range. Frequent and rapid temperature changes (thermal shock) result in additional thermal stresses. It is no coincidence that in this regard, the appearance of various kinds of defects (destruction of the material due to loss of heat resistance, accumulation of structural defects and the development of fatigue cracks, corrosion, thermal fatigue, destruction during contact interaction of parts) in the overwhelming majority of cases is observed in a thin surface layer of parts, which is the primary reason for a decrease in the total strength and destruction of parts in operation. [2].

The manufacturing technology of compressor blades and turbines of an aircraft gas turbine engine is a very complex technological process. Due to the complication of the design of the blades, requiring modern manufacturing technologies and technologies to increase durability, the costs of their manufacture increase. The service life of the compressor and turbine directly depends on the design, technological and operational factors.

Typically, TBC (Thermo barrier coating) is a two-layer system (Figure 4) that includes a ceramic topcoat layer about 250 μm thick on the outer surface of the substrate and a metal bond coat layer about 150 μm thick. The metal bond coating performs two functions:

- For oxidation resistance and
- For physical and chemical bonding of ceramics to superalloy substrates.

The oxide that is commonly used is zirconium oxide (ZrO_2) and yttrium oxide (Y_2O_3). The metal bond coating is an oxidation/hot corrosion resistant layer. The bond coating is empirically represented by the MCrAlY alloy.

Where,

M - metals such as Ni, Co or Fe

Y - Active metals such as yttrium

Cr-Al - base metal.

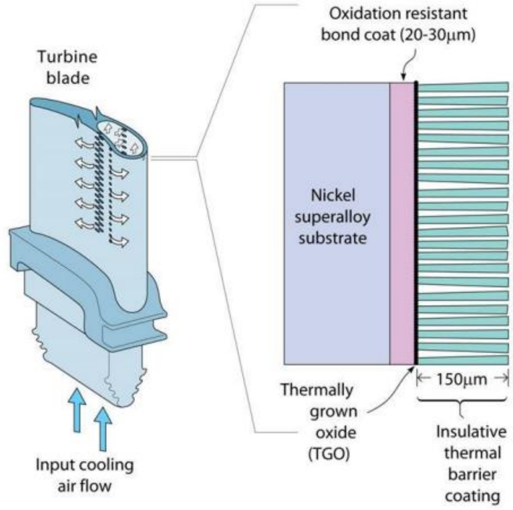

Figure 4 – Structure of thermal barrier coatings.

The bond coat is typically a metal layer made of a nanostructured NiCoCrAlY cermet composite layer on a metal substrate and is responsible for creating a second thermally grown ceramic oxide coating layer that occurs when the coating is subjected to elevated temperature.

When aluminum oxide and nitride nanoparticles are distributed over the binder coating or over its surface, the formation of thermally grown oxides is catalyzed. This ceramic layer is responsible for forming a uniform thermal barrier, acting as an oxygen scavenger that prevents thermal oxidation of the substrate. The top (last) coating layer is a ceramic top layer, which consists of a top layer of $La_2Ce_2O_7$ ceramic composite. The top layer protects the substrate by keeping the other layers of the coating below the surface temperature. [14]

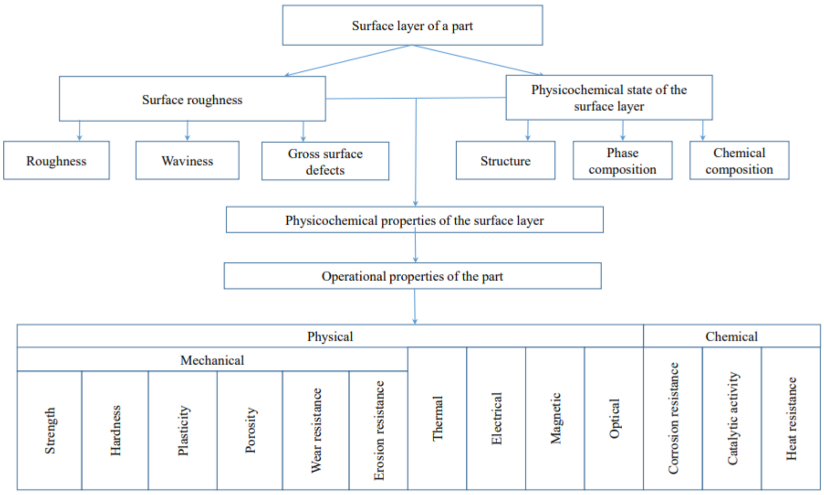

Figure 4 – The relationship of the surface layer with the performance properties of parts.

To increase the durability, a heat-resistant coating is applied to the blade, then an intermediate (so-called transition layer), on this layer a ceramic coating is formed. Such processes are very complex and the quality of the formed layer depends on the control of technological processes for the deposition of thermal barrier coatings. The process of forming thermal barrier coatings on the surface of turbine blades is carried out in a special ion-plasma installation. Before spraying, the blades are loaded into a chamber, from which air is evacuated with a vacuum pump. On the surface of the evaporated electrode (cathode), from which the coating material is made, so-called cathode spots with a thickness of several microns are formed. This allows the material to evaporate without forming a liquid phase. That is, the composition of the coating material is transferred in the form of a plasma flow to the surface of the part, forming a layer that is constantly compacted by charged metal particles that are present in the plasma. The body of the blade is evenly covered from all sides with a protective layer of a special composition 0.1 microns thick. The spatula can be applied as many coats as needed. These coatings provide protection for the blades under thermal cycling conditions.

For the process of plasma spraying in a vacuum, the main factors influencing the formation of coatings, their physical, mechanical and operational properties are the preparation of the surface of products for spraying, the energy of the sprayed particles, the condensation temperature and residual stresses. Moreover, thermal phenomena and residual stresses play the most significant role in the formation of coatings. The coatings can be destroyed both during the spraying process and after it. It is possible to avoid such phenomena and obtain coatings with specified physical and mechanical properties by controlling their composition and technological mode of formation.

The quality and reliability of heat-resistant, ceramic heat-shielding coatings on GTE turbine blades largely depends on the stress state in the "coating-substrate" system. Therefore, the study of the magnitude and sign of residual stresses in the coating and substrate is of great practical interest.

A number of works [4, 5, 8, and 9] are devoted to the development of computational and experimental methods for determining residual stresses and studying residual stresses in coatings of stoichiometric and non-stoichiometric composition.

It is shown that an important area is the study of residual stresses in multicomponent and multilayer coatings, as well as in coatings of non-stoichiometric composition. The latter will make it possible to expand the areas of their application, including due to the possibility of varying the stress state in the "coating-substrate" system.

The stress-strain state of turbine blades has been studied in the literature [10]. Residual stresses due to temperature changes can cause plastic deformation of GTE parts. For these reasons, the behavior of the material during engine operation is unlikely to be non-linear, and the simulation results are time-consuming. This article presents the results of a study on the selection and implementation of some advanced methods for assessing the service life of materials for elements of gas turbine engines.

The proposed method for calculating and predicting stresses in multilayer and multicomponent coatings on GTE turbine blades takes into account various combinations of materials of both the substrate (blade material) and protective layers (thermal barrier, transition layers, as well as a layer in contact directly with the blade surface). Not only are the mechanical characteristics of materials (modulus of elasticity and Poisson’s ratio) taken into account, but also thermophysical properties (coefficient of linear expansion). When calculating, the thickness of each layer, its temperature and physical and mechanical properties can be set within wide limits.

Based on the developed mathematical model for calculating residual stresses on turbine blades with multilayer protective coatings, we have compiled a program in the C++ language for n-layers [6]. The calculation also takes into account the physical and mechanical properties of the material of the turbine blade.

Conclusion: Based on the study, the following conclusions can be drawn.

1. The composition and structure of heat-shielding coatings on the working surfaces of the turbine blade has a significant effect on the gas temperature in front of the turbine. It is important to study the physical and mechanical properties of turbine blades with thermal barrier coatings and the behavior of the system under thermal cyclic loads;

2. The use of adequate methods for diagnosing the stress-strain state of the turbine blades ensure high reliability of the aviation GTE as a whole.

References

1. V.G. Vorobyev, V.D. Konstantinov. Nadejnost i tekhnicheskaya diagnostika aviatsionnogo oborudovaniya: uchebnik. M.: MGTU GA, 2010. 448 p.
2. V.S. Muhin, A.M. Smislov. Injineriya poverxnosti detaley mashin// Vestnik UGATU T.12, № 4(33). P. 106-112.
3. A.M. Sulima, V.A. Shulov, Yu.D. Yagodkin. Poverxnostniy sloy i eksplutatsionniye svoystva detaley mashin. M.: Mashinostroeniye, 1988. -240 p.
4. R.Kh. Saydakhmedov, Yu.D. Yagodkin, M.G. Karpman, M.V. Kostina. Issledovaniye napryajennogo sostoyaniya v ionno-plazmennix pokrytiyax// Materiyalovedeniye. 2002. №8. P.12-16.
5. R.Kh. Saydakhmedov, D.R. Kadirova. Raschetno-eksperimentalnoye issledovaniye ostatochnyx napryajeniy v ionno-plazmennyx pokrytiyax na osnove titana, sirkoniya, niobiya i ix nitridov// Oborudovaniye i texnologii termicheskoy obrabotki metallov i splavov (Tom 2) (Sbornik dokladov IX Mejdunarodnogo nauchno-texnicheskogo kongressa termistov i metallovedov). - Kharkov: NNS XFTI, 2008. P. 26–30.
6. R.Kh. Saydakhmedov, G.R. Saidakhmedova. Raschet ostatochnyx napryajeniy na lopatkax turbin gazoturbinnogo dvigatelya// Svidetelstvo programmnogo produkta dlya elektronno-vychislitelnix mashin. №DGU 12690. 15. 10. 2021.
7. Yu.A. Tamarin, E.B. Kachanov. Noviye texnologicheskiye prosessy GTD, Moskva 2008 – P. 144–158.
8. G.P. Fetisov, M. G. Karpman, R.Kh. Saydakhmedov. Ionno-plazmennye nestexiometricheskiye pokrytiya na osnove nitridov i karbidov perexodnyx metallov. – M.: Izd-vo MAI-PRINT, 2011. –220 p.
9. Saydakhmedov R.H., Khamraeva G.A., Khamraqulov U.Sh. Computer-aided modeling of vacuum coatings stressed state//Conference Proceedings MITA 2015 The 11th International Conference on Multimedia Information Technology and Applications (MITA 2015) June 30-July 2, 2015, Tashkent, Uzbekistan. P. 244-247.
10. Vincenzo Cuffaro, Francesca Curà, Raffaella Sesana., Advanced life assessment methods for gas turbine engine components, Procedia Engineering, Volume 74, 2014, Pages 129-134, XVII International Colloquium on Mechanical Fatigue of Metals (ICMFM17), Politecnico di Torino, Italia.
11. A.S. Komshin, V.I. Pronyakin. Modern Diagnostics of Aircraft Gas Turbine Engines // Bauman Moscow State Technical University, Moscow, Russia, IOP Conf. Series: Materials Science and Engineering 714 (2020);
12. A.V. Kochergin, N.V. Pavlova, K.A. Valeeva. Vibroacoustic control of Technical conditions of GTE // Procedia Engineering 150: 363-369 p. December 2016.
13. B. Vasilyev. Stress–strain state prediction of high-temperature turbine single crystal blades using developed plasticity and creep models // Turbine Technical Conference and Exposition GT2014 June 16–20, 2014, Düsseldorf, Germany.
14. A. Aabid, S.A. Khan, Optimization of Heat Transfer on Thermal Barrier Coated Gas Turbine Blade // IOP Conf. Ser.: Mater. Sci. Eng. 370, 2018].