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FINISHING METHODS FOR GTE BLADES TO INCREASE THEIR SERVICE LIFE

Purpose. *The purpose of the work is to analyze modern approaches and methods, extend the service life of compressor blades of gas turbine engines through the use of various individual and complex methods of surface treatment of parts. The final result of this analysis is a summary of data on the effectiveness of the individual use of each method separately and the effectiveness of the combined use of two or more methods simultaneously or sequentially. Based on the results of the summary, conclusions were made on the rationality of using complex approaches and directions for new research in the future were identified.*

Research methods. *Literary sources were selected using the Google Scholar and Scopus bibliographic databases. The keywords for the search were «methods for strengthening blades», «complex technologies», «thermal methods», «chemical methods», «nitriding», «total resource», and «GTE compressor» in Ukrainian and English.*

Results. *The main result of the work is a clear and detailed generalization and comparative analysis of the main methods of strengthening the blades of gas turbine engines. This generalization clearly demonstrates the advantages of using integrated approaches. The synergy effect of the simultaneous use of several technologies is considered in detail and confirmed by the results of reports on practical use and laboratory studies published by domestic and foreign scientists.*

Scientific novelty. *A comprehensive systematization and comparative analysis of the effectiveness of individual and combined methods of surface treatment of gas turbine engine (GTE) blades has been performed, taking into account the depth of strengthening, resource increase, technological compatibility, and practical feasibility. A structured approach to assessing the synergistic effect of combinations of different methods (mechanical, chemical-thermal, thermal, ion-plasma) has been proposed, with the most effective technological combinations being identified. It is substantiated that the use of such combinations provides an increase in resource by 400–500% without changing the geometry of the part or base material, which opens up new opportunities for their implementation in serial production and repair of aviation equipment.*

Practical value. *The results of the work can be used by engineers and researchers to familiarize themselves with modern diverse methods of increasing the resource of GTE scrap, the effectiveness of these methods, and the advantages of comprehensive approaches to the use of these methods in GTE production.*

Key words: *methods for strengthening blades, complex technologies, thermal methods, chemical methods, nitriding, total resource, gas turbine engine.*

Introduction

The working blades of a gas turbine engine (GTE) operate in harsh conditions: high temperatures, loads, contact with aggressive environments. As a result, damage occurs on their surfaces over time—fatigue cracks, erosion, wear, which limits their service life and increases the risk of accidents. To extend the service life of the blades, it is necessary to increase their fatigue strength and wear resistance. In modern conditions, when using aircraft engines, it is critical to reduce their cost, operating costs, and maximize their efficiency. One way to achieve this is to increase the service life of gas turbine engine blades. At the same time, in order to reduce the cost of such modernization, it is necessary to avoid significant changes in the design and materials of the blades as much as possible.

The above issues dictate the need for an in-depth study of the effectiveness of existing methods of surface treatment of gas turbine engine blades.

Purpose of the work

The purpose of this review is to analyze modern approaches and methods for increasing the service life of gas turbine blades with various individual and comprehensive methods of their surface treatment. The result of this analysis is a summary of data on the effectiveness of the individual use of each method separately and the effectiveness of the combined use of two or more methods simultaneously or sequentially. Based on the results of the summary, conclusions were made on the rationality of using complex approaches and directions for new research in the future were identified.

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Material and methods of research

The selection of literature sources was carried out using the bibliographic databases Google Scholar and Scopus. Keywords for the search were: “methods of strengthening the blades”, “complex technologies”, “thermal methods”, “chemical methods”, “nitriding”, “general resource of service”, “GTE compressor” in Ukrainian and in English.

Discussion

Conventionally, all existing methods that are used for treating the surfaces of the blades of the GTE for increasing the service resource can be divided into several groups according to the methods of influencing the material of the blade surface.

Mechanical treatment using plastic deformation of the material of the surface: Table 1 summarizes the main mechanical methods of surface treatment of the GTE blades using plastic deformation. The data was obtained by analyzing scientific publications and technical reports. The greatest hardening depth and service life extension are demonstrated by hardening method known as the Laser Shock Peening (LSP). This is a method of creating residual compressive stresses in the surface layer, which is deformed by a micro-blast wave from a micro-explosion of plasma on the surface of the part. Plasma is created as a result of a short, high-energy laser impulse. This creates internal compressive residual stresses in a layer of material up to 1.0 mm deep. These stresses slow down the development of fatigue cracks and significantly increase cyclic durability [15].

Shot peening and ultrasonic treatment are less effective but widely used methods due to their ease of implementation. The choice of method depends on operating conditions and durability requirements.

Chemical-thermal treatment. In the course of further analysis, chemical-thermal treatment methods were analyzed. Since this analysis concerns GTE blades, boriding can be selected for titanium alloys as the most effective among conventional chemical-thermal surface treatment technologies.

Boriding can provide the highest hardness up to 2000 HV, forming a thick layer (up to 0.8 mm) that is resistant to erosion and abrasive wear.

Table 1 – Main mechanical methods of compressor blade surface treatment using plastic deformation

Treatment method	Hardening layer depth, mm	Increase of general resource of service, %
Shot (Peening)	0.1–0,3	30–50 [4]
Deep rolling	0.5–1.0	Up to 100 [1],[17]
Laser Shock Peening	0.6–1.2	Up to 150 [3],[15]
Low plasticity Burnishing	0,6-1,0	200+ (Depending on the alloy) [5]
UIT	0,3-0,8	200+ [6] (Depending on the material)

Table 2 – Increase of the general resource depending on the depth of the reinforced layer after boriding.

Method	Depth of the reinforced layer, мм	General resource increase, %
Boriding [8]	Up to 0,07	80–150

Thermal and thermomechanical treatment. To ensure high reliability and durability of gas turbine engine (GTE) blades, one of the critically important areas is the use of thermal and thermomechanical treatment methods. Table 3 summarizes the results of the analysis of thermal and thermomechanical treatment methods for GTE blades and the selection of the three most commonly used methods that have demonstrated the greatest effectiveness in aviation engine manufacturing, particularly during serial production and blade repair.

Analysis of the main existing methods and selection of the most common and most effective ones: hot isostatic pressing (HIP) is one of the most effective methods for strengthening blades manufactured by casting or additive technologies. This method eliminates internal porosity, microcracks, and defects characteristic of the initial state of the blank. HIP provides volumetric strengthening of the part, as evidenced by an increase in overall service life of up to 90 % [10]. The method is widely used in practice by manufacturers such as Rolls-Royce, GE Aviation, and Motor Sich JSC.

Aging after preliminary hardening is a thermal method that ensures the formation of dispersed strengthening phases in the alloy structure (in particular, in β-titanium alloys such as VT22 and Ti-6Al-4V). This approach gives a significant increase in fatigue strength, allows stabilization of material properties during long-term usage, and reduction of the rate of damage accumulation [13, 16]. The increase in general resource due to a properly selected aging regime reaches 100%, which is one of the highest indicators among classical thermal processes.

Thermomechanical aging combines plastic deformation of the material of the surface (up to 5–10 %) with subsequent thermal aging at the aging temperature. This approach not only allows the formation of strengthening phases, but also additionally increases compaction of the surface layer and reduces the grain size. The method is particularly effective in strengthening areas working under concentrated loads, such as the root of the blade. The increase in service life under such conditions is up to 50 %, and the depth of strengthening is 0.8–1.5 mm [13].

Vacuum annealing [10] allows effective reduction of internal stresses after mechanical treatment while maintaining the chemical purity of the surface, which is particularly important for subsequent ion-plasma coating.

Isothermal tempering [14] is used for thermal stabilization of the structure in heat-resistant alloys. This improves creep resistance and preserves mechanical properties at continuous operating temperatures, which is relevant for GTE blades.

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Thus, the most effective and practically significant methods for increasing the service life of GTE blades are hot isostatic pressing, aging after hardening, and thermomechanical aging. These technologies combine high service life increase, availability for implementation in production, and compatibility with modern materials –titanium, nickel, and heat-resistant steels.

Table 3 – Generalized results of the analysis of methods of thermal and thermomechanical treatment of GTE blades

Method	Layer depth, мм	General resource growth, %
Hot isostatic pressing (HIP)	Full volume	Up to 90 (depending on the alloy) [9],[10]
Aging after hardening	Full volume	Up to 100 (depending on the alloy) [11],[12]
Thermomechanical aging	0.8–1.5	Up to 100 (Depending on the alloy) [13],[14]

Laser and ion-plasma methods: this group of processing methods is one of the ways to increase the durability of blades using laser and ion-plasma technologies, which allow improving performance characteristics without changing the geometry of the product or the structure of the base material.

The most effective methods in this group include:

Ion-plasma nitriding is a process of saturating the surface layer with nitrogen in an electric plasma environment. This promotes the formation of solid nitride phases with high wear resistance and hardness (up to 1200 HV). As shown in [7, 16], the service life of blades after nitriding increased by an average of 50–80 % depending on the engine operating mode.

Ion-plasma coating (PVD, CVD) – unlike previous methods, this method involves the application of thin functional coatings (TiN, AlTiN, CrN) with high adhesion to the substrate. The method provides increased erosion resistance when operating at high temperatures. [2]

Table 4 – Results of analysis of laser and ion-plasma processing methods

Method	Layer depth, мм	Resource increase, %
Ion-plasma nitriding	0,01–0,05	Up to 80
Ion-plasma coating (PVD)	0,002–0,010	Up to 50 (depending on the coating)

Analysis of the effectiveness of the complex use of methods for treating the surfaces of the blades of the GTE

The first part of the article was devoted to the analysis of existing methods of surface treatment of GTE blades to increase their service life. The effectiveness of these methods under individual use conditions was analyzed. Today, one of the main promising areas of development of blade production technology is the study of the effectiveness of complex use of these technologies. This approach makes it possible not only to combine several methods, but also to achieve a synergistic effect through the sequential or simultaneous application of several physical and chemical processes to the surface of the part, resulting in multiple times increase in general effectiveness.

Below are graphs showing the effectiveness of the complex use of the methods described in the article in various combinations. Further study of the technological experience that exists today was aimed directly to finding the most effective combinations. Eleven existing technologies were analyzed, classified in the previous part of the article by direction: mechanical processing using plastic deformation of the surface material of the part, chemical-thermal processing, thermal and thermomechanical processing, laser and ion-plasma methods. Based on a multifactorial analysis of efficiency, hardening depth, technological compatibility, and practical implementation, five most promising combinations were formed:

1. LSP (Laser Shock Peening) + PVD – laser shock peening combined with ion-plasma spraying of thin hard coatings (Fig. 1). When these treatment methods are used in combination, a synergistic effect is observed and the overall service life of the GTE compressor blade increases by up to 300 %, depending on the blade material.

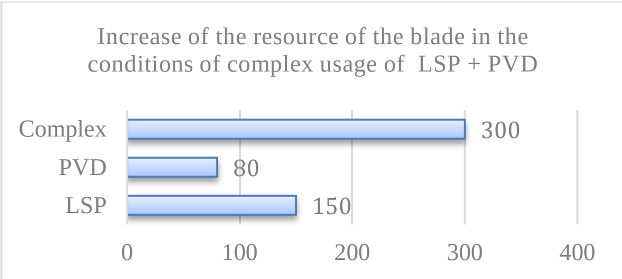

Figure 1. Resource increase when using LSP + PVD

2. LSP (Laser Shock Peening) + Ion-Plasma Nitriding – mechanical strengthening and diffusion saturation of the surface with nitrogen (Fig. 2). When these treatment methods are used in combination, a synergistic effect can also be observed, resulting in an increase in the service life of the GTE blade up to 300 %

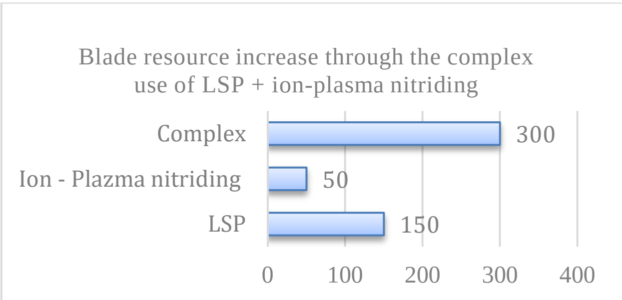

Figure 2. Blade resource increase through the complex use of LSP + ion-plasma nitriding

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3. HIP (Hot Isostatic Pressing) + Ion-Plasma Nitriding – hydrostatic compaction of the internal structure and increased hardness of the surface layer of the blade material (Fig. 3). This combination of methods implements a structurally complex approach to increasing the service life of GTE blades. HIP eliminates internal defects (pores, cracks) that can become centers of fatigue failure, while nitriding creates a hard protective layer that is highly resistant to wear, erosion, and oxidation. This is especially relevant in the production of blades by casting or 3D printing, as well as in blade restoration.

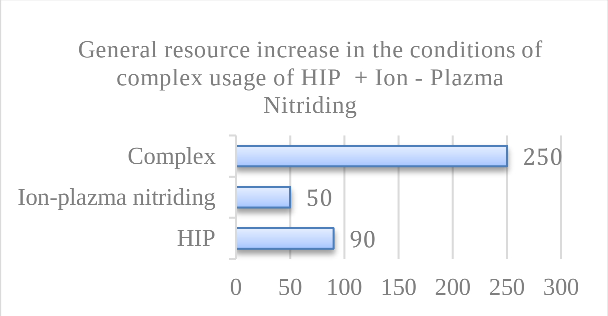

Figure 3. General resource increase in the conditions of complex usage of HIP + Ion -Plazma Nitriding

4. HIP (Hot Isostatic Pressing) + Thermomechanical Aging (TMA) – structural stabilization and reduction of internal stresses (Fig. 4). The combinat of HIP + thermomechanical aging is an effective strategy for improving the internal structure and increasing the fatigue strength of blades. Unlike surface methods, this technique works at a deeper level, strengthening the entire part. This is particularly effective for cast or additively manufactured blades made of titanium and nickel alloys.

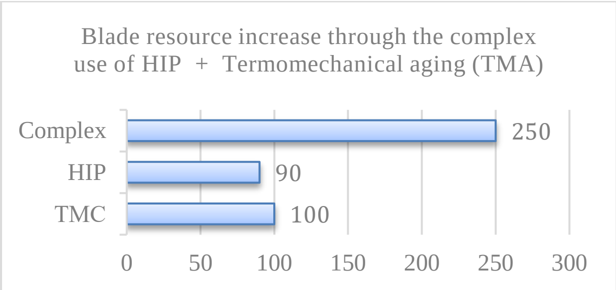

Figure 4. Resource increase through complex usage of HIP + TMA

5. LSP (Laser Shock Peening) + PVD (Ion-Plasma Deposition) + Ion-Plasma Nitriding – a three-component combination that provides comprehensive strengthening (Fig. 5). This combination is the most effective in terms of increasing the service life of GTE blades. There is a powerful synergistic effect. Synergy mechanism: LSP creates deep residual compressive stresses (~1 mm deep), which inhibits the growth of fatigue cracks, nitriding forms a chemically stable and superhard layer with a hardness of up to 1200 HV, PVD applies a wear-resistant coating (TiN, CrN, AlTiN, etc.), which increases resistance to erosion, oxidation, and corrosion.

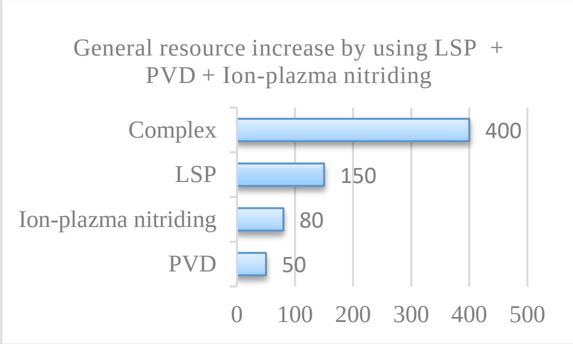

Figure 5. General resource increase by using LSP + PVD + Ion plasma Nitriding

Conclusions

As a result of this research, 13 modern technological methods for strengthening gas turbine engine (GTE) blades were analyzed. Mechanical, chemical-technical, chemical-thermal, thermal, laser, ion-plasma methods, as well as coating application methods were evaluated.

All selected processing methods act at different levels: from submicrostructure (LSP) to the chemical composition of the surface layer (nitriding, coating). Methods that create surface deformation of the blade material form compressive stresses up to 0.3 mm deep. This strengthens the surface layer due to work hardening and orientation of the material structure, which increases strength and prevents the initiation and development of fatigue cracks. Changing the chemical composition of the surface layer of the material, for example, diffusion nitriding, increases the surface hardness to 1000–1100 HV. PVD coatings with TiN or CrN act as a barrier against wear and oxidation. The blade surface is subject to diverse influences. This diversity and sequence creates synergy effects.

Of the five processing methods, three with the highest potential for application in the aviation industry were selected:

LSP + Nitriding – demonstrated effectiveness in increasing fatigue strength. Published studies have shown an increase in cycles to failure from 8×10^3 to 2×10^5 at a load of 450 MPa.

LSP + PVD + Nitriding – combines mechanical strengthening, chemical-thermal saturation and the application of a hard wear-resistant layer. The increase in total resource is up to 400% (depending on the material) compared to raw samples

HIP + Nitriding – Provides compaction of cast or printed structure and formation of a solid surface layer. This method increases the resource by up to 300 % and has proven itself in the production of large GTE blades.

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ФІНІШНІ МЕТОДИ ОБРОБКИ ЛОПАТОК ГТД ДЛЯ ПІДВИЩЕННЯ ЇХ РЕСУРСУ

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Мета роботи. *Метою роботи є проведення аналізу сучасних підходів та методів, збільшення ресурсу компресорних лопаток ГТД через використання різних індивідуальних і комплексних методів обробки поверхні деталей. Кінцевим результатом цього аналізу є узагальнення даних по ефективності індивідуального використання кожного з методів окремо і ефективності комбінованого використання двох і більше методів одночасно або послідовно. По результатам узагальнення зроблені висновки по раціональності використання комплексних підходів та означені напрямки нових досліджень в майбутньому.*

Методи дослідження. *Підбір літературних джерел здійснювався з використанням бібліографічних баз Google Scholar та Scopus. Ключові слова для пошуку були «методи зміцнення лопаток», «комплексні технології», «термічні методи», «хімічні методи», «азотування»,» загальний ресурс», «компресор ГТД» українською та англійською мовами.*

Отримані результати. *Основним результатом роботи є чітке і детальне узагальнення і порівнювальний аналіз основних методів зміцнюючей обробки лопаток ГТД. Вказане узагальнення обґрунтовано показує перевагу*

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використання комплексних підходів. Детально розглянуо ефект синергії при одночасному використанні декількох технологій і підтверджується це результатами звітів по практичному використанню і лабораторних досліджень, які опубліковані вітчизняними та іноземними науковцями.

Наукова новизна. *Виконано комплексну систематизацію та порівняльний аналіз ефективності індивідуальних і комбінованих методів поверхневої обробки лопаток газотурбінних двигунів (ГТД) з урахуванням глибини зміцнення, приросту ресурсу, технологічної сумісності та практичної реалізованості. Запропоновано структурований підхід до оцінки синергетичного ефекту від комбінацій різних методів (механічних, хіміко-термічних, термічних, іонно-плазмових) з відокремленням найбільш результативних технологічних поєднань. Обґрунтовано, що використання таких комбінацій забезпечує підвищення ресурсу до 400–500% без зміни геометрії деталі чи матеріалу основи, що відкриває нові можливості для їхнього впровадження у серійне виробництво та ремонт авіаційної техніки.*

Практична цінність. *Результати роботи можуть використовуватись інженерами та науковими співробітниками для ознайомлення із сучасними різноплановими методами підвищення ресурсу ломаток ГТД, ефективністю цих методів та з перевагами комплексних підходів до використання цих методів у виробництві ГТД.*

Ключові слова: *методи зміцнення лопаток, комплексні технології, термічні методи, хімічні методи, азотування, загальний ресурс, газотурбінний двигун.*

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