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Methods of increasing the service life of gas turbine engine turbine blades

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Abstract: The article discusses methods for increasing the service life of turbine blades of gas turbine engines (GTE). These blades are important components operating at high temperatures and loads, and various technologies are used to increase their durability. The main methods include the application of hardening coatings, the use of new heat-resistant materials, and chemical and physical coating technologies. In the aviation industry, the issues of improving the efficiency of aircraft engines and their long-term operation are of significant importance. The service life of each aviation engine, its maintenance, and operational costs primarily depend on the strength of its main components. This is especially true for turbine blades, which are among the most loaded parts of a gas turbine engine, as they operate under extreme temperature and stress conditions. At temperatures of 1500°C and above, the blades can be subjected to deformation or damage due to high thermal and mechanical stresses. Methods such as PVD and CVD are used to apply high-temperature and corrosion-resistant coatings to the surface of the blades, which ensures their long-term and efficient operation. The article also provides detailed information on the advantages of these coating technologies and their impact on turbine components.

Keywords: substrate, blade, gas turbine engine, main components, corrosion-resistant, coating

1. Introduction

A gas turbine engine (GTE) is a device that converts the chemical energy of fuel into mechanical energy through combustion. The main operating principle of a GTE is as follows: air is compressed in a compressor, mixed with fuel in the combustion chamber, ignited, and the expanding gases rotate the turbine, performing useful work. Gas turbine engines are widely used in aviation, power generation, shipbuilding, and industry.

The components of a gas turbine engine operate under extremely harsh conditions, so they are subject to very high requirements. Especially important characteristics include heat resistance, retention of strength at high temperatures, and resistance to corrosion.

The components of a gas turbine, especially turbine blades, operate at very high temperatures. Since these parts are in direct contact with the gases formed during fuel combustion, the materials from which they are made must have high heat resistance. To improve engine efficiency, it is important to maximize the gas temperature before the turbine while preventing part deformation.

Gas turbine components operate at temperatures of 1000–1500 °C and higher, so resistance to deformation is critical. Heat resistance is the ability of a material to deform slowly under mechanical stress when exposed to high temperatures for an extended period.

2. Research methodology

Turbine parts in direct contact with hot gases function in a highly oxidizing and chemically active environment. This is due to the effects of oxides, sulfides, and other harmful chemical compounds formed during fuel combustion. Corrosion can significantly reduce the service life of GTE components and weaken their structural integrity. Figure 1 shows a general view of a gas turbine engine.

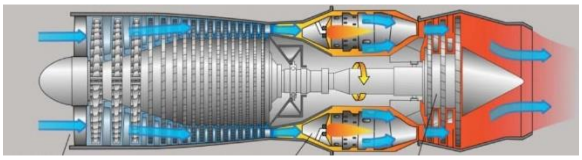

Figure 1. General view of a gas turbine engine (GTE)

Main Advantages of Using Gas Turbine Engines (GTE) in Aviation:

1. Gas turbine engines are lightweight and have high power output. Therefore, they are widely used in aviation.
2. At high operating temperatures, efficiency increases, which reduces fuel consumption and makes the engine more powerful. Modern GTEs operating at elevated temperatures are especially more efficient.
3. A gas turbine can operate at very high rotational speeds, which ensures fast and efficient energy production.
4. Gas turbines are very compact and do not require much space, making them ideal for use in aviation and military technology.
5. GTEs have few moving parts inside, which reduces vibration levels. This contributes to longer service life.
6. Gas turbine engines can operate efficiently on various types of fuel, including natural gas, kerosene, and other liquid fuels.

Disadvantages:

1. For efficient operation, a GTE must function at very high temperatures. This requires materials with high thermal resistance, which increases manufacturing costs.
2. Gas turbine engines require complex and expensive technologies. Their production and maintenance demand significant investment.
3. GTEs lose efficiency at low loads. When operating under low load conditions, fuel consumption increases significantly.
4. Components operating under high temperatures and stresses can wear out or become damaged over time, requiring costly and complex maintenance.

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5. Due to the high temperatures, GTE cooling systems become complex and sensitive. Internal cooling channels and thermal coatings help address this issue, but their production and repair add to the overall costs.

6. GTEs require high-quality fuel. With low-quality fuel, efficiency decreases and the risk of corrosion increases.

Relevance of Using Gas Turbine Engines (GTE):

Aircraft Engines: GTE technology is a crucial part of aviation. Most turbofan, turbojet, and turboprop engines in aircraft are based on gas turbine technology. For aircraft engines, high power and compact size are essential, which highlights the advantages of GTEs.

Fuel Efficiency: Next-generation gas turbine engines have high fuel efficiency, allowing airlines to reduce fuel consumption and decrease harmful emissions into the atmosphere.

Low Noise and Vibration Levels: Gas turbine engines produce relatively low noise and vibration levels, contributing to the ease and comfort of operating aircraft.

What Methods Can Increase the Service Life of Gas Turbine Blades?

It is crucial to extend the service life of gas turbine engine (GTE) blades, as they operate under high temperatures, pressures, and in an aggressive environment. Blades are expensive and complex components, so prolonging their lifespan enhances the overall efficiency and reliability of the engine.

Protective Coatings for Turbine Blades to Extend Service Life

Why Apply Coatings?

The technology of protecting turbine blades with coatings helps significantly extend the service life of a gas turbine engine (GTE). The turbine blades operate in environments exposed to high temperatures from gas flows and aggressive conditions, which is why they are protected by special coatings that offer high thermal resistance and corrosion resistance.

Various coating application technologies are used to protect turbine blades and other GTE components. Each type of coating serves specific protective functions and significantly increases the material's service life. Thermal barrier coatings, coatings resistant to oxidation and corrosion, diffusion coatings, and multilayer coatings are considered the most effective. These coatings play an important role in enhancing the efficiency of the gas turbine and reducing maintenance costs.

Corrosion-Resistant Coatings

In aggressive environments, especially when interacting with high-temperature chemicals, material protection against corrosion is required. Alloys based on aluminum (Al), chromium (Cr), and platinum (Pt) are used for corrosion protection. These coatings are applied to protect any turbine parts that may be affected by heat and fuel combustion.

Oxidation-Resistant Coatings. It is very important to prevent the oxidation process of materials in high-temperature environments. Oxidation-resistant materials such as aluminum (Al), chromium (Cr), and others are used for this purpose. Oxidation-resistant coatings are primarily applied to turbine blades and combustion chambers.

Diffusion Coatings. These coatings alter the chemical properties of the material, enhancing its strength and resistance to corrosion and oxidation. Aluminum coatings are used for this task. At high temperatures, aluminum oxidizes to form an aluminum oxide (Al2O3) layer, which protects the material. Platinum coatings improve the material's heat resistance and its protection against oxidation. These coatings are widely used to strengthen both the internal and external parts of turbine blades.

Multilayer Coatings. These coatings consist of several protective layers, each serving its own function. For example, the inner layer may protect against oxidation, while the outer layer provides thermal protection. Such coatings are applied to GTE components that operate in the most complex and demanding conditions. The table below presents some of the micro-hardening compositions used as coatings (Table-1).

Table 1

Microhardness of carbides and nitrides

Coating material	Cr2C2	TiN	TiC	Mo_2C	TaN
Microhardness	33	35.7	16	26.7	27
Coating material	TaC	ZrN	ZrC	VC	VN
Microhardness	38.6	25	27	18.5	29

Carbides (e.g. WC, TiC) are compounds of carbon with metals.

Nitrides (e.g. TiN, AlN) are compounds of nitrogen with metals.

Presents the chemical composition of multicomponent heat-resistant coatings. These coatings are widely used in **aviation engines. (Table 2)**

Table 2

Chemical Composition of Multicomponent Heat-Resistant Coatings

Coating type	Concentration of elements, %			Concentration of elements, %		
	Ni	Co	Cr	Al	Ti	Others
Ni-Co-Cr-Al-Y	60,4	10,2	12,4	16,0	0,5	0,5Y
Ni-Co-Cr-Al-Y	35,5	33,2	25,4	4,9	-	1Y
Co-Cr-Al-Y	-	63,6	22,9	12,7	-	0,8Y
Ni-Cr-Al-La-Y	56,2	2,5	32,1	5,6	0,7	0,8Y
Ni-Cr-Fe-Si-B	62,8	-	29,0	-	-	4,6Si; 3,5Fe; 0,05B

Various technological methods are used to obtain coatings. Among them are physical and chemical methods for applying protective coatings. Let's examine these methods below.

PVD (Physical Vapor Deposition) is a coating technology that uses physical evaporation, where solid materials (metals or ceramics) are evaporated in a vacuum environment and then condense onto the surface of the coating. This is a method for applying thin layers of material (1–5 microns) without chemical reactions, relying solely on physical processes (evaporation). This method is widely

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used in aviation, mechanical engineering, and other industries.

The evaporation of a solid material occurs by heating it in a vacuum chamber. The evaporated material condenses on the substrate (base surface), forming a thin, uniform, and durable coating. The evaporation and condensation process takes place in a vacuum, which prevents contaminants from the air from entering the coating. Materials such as TiN (titanium nitride), CrN (chromium nitride), AlTiN (aluminum-titanium nitride), and ZrN (zirconium nitride) can be synthesized. Ceramic-based materials are used to create coatings resistant to heat and corrosion. Coatings based on a mix of metals and ceramics are used to improve mechanical and physical properties.

The PVD technology offers wide opportunities for creating high-quality and durable coatings. The use of PVD coatings in aviation and other industries enhances the durability of components, increases their resistance to wear and corrosion, and contributes to improved cost-effectiveness.

Table 3

Principles of Coating Application and Use of PVD Methods

PVD Method	Principle	Application	Advantages	Disadvantages
Magnetron Sputtering (Sputter Deposition)	Argon ions strike the surface, directing atoms onto the substrate.	TiN, CrN, Al_2O_3 coatings	High-quality thin layers	Low deposition rate (1–3 µm/hour)
Arc Evaporation	An electric arc evaporates the surface, creating plasma.	TiAlN, ZrN (for hard cutting tools)	Very hard layers (~3000 HV)	Microdroplets (surface defects)
Electron Beam (EB-PVD)	An electron beam melts the surface, forming vapor.	Turbine blade coatings	Thick layers (10–100 µm)	Requires high temperature (>600°C)
Pulsed Laser Deposition (PLD)	A laser interacts with the surface, forming vapor.	Oxides (MgO, ZnO), superconductors	Nanocomposites with precise composition	Expensive and slow process
Ion Plating	Material is ionized and deposited onto the substrate.	Widely used in aviation	Coatings with high hardness and adhesion	Requires specialized and complex equipment

CVD (Chemical Vapor Deposition) is a method of obtaining coatings through chemical vapor deposition, which is widely used for producing hard coatings, ceramic materials, and coatings resistant to high temperatures. This technology involves the deposition of solid materials in the form of thin or thick layers onto the surface of a substrate through chemical reactions in the gas phase. The process typically takes place at high temperatures (800–1000°C) and low pressure. The CVD technology is applied in various industries, particularly in aviation, microelectronics, optics, and the production of hard materials.

Special gases, typically consisting of metal or ceramic precursors (reactive substances), are introduced into the reactor chamber. These gases settle on the surface of the substrate and initiate chemical reactions. Under the influence of high temperature, the gases react chemically. As a result of this reaction, a solid material is deposited onto the substrate, forming a coating. Usually, these are metals, carbides, nitrides, or oxides. By-products of the reaction (usually in gas form) are removed from the reactor chamber without affecting the quality of the coating.

The CVD technology allows for the production of high-quality and durable coatings; however, it requires high temperatures and expensive equipment. Nevertheless, due to its widespread application and numerous advantages, CVD technology plays an important role in industry and scientific research.

Table 4

Principles of Coating Application and Use of CVD Methods

CVD Type	Principle	Advantages	Disadvantages	Application
Atmospheric Pressure CVD (APCVD)	CVD process carried out at atmospheric pressure.	Cheaper, can coat large parts.	Coating may be uneven.	Mass production, optics, electronics.
Low Pressure CVD (LPCVD)	CVD process carried out at low vacuum pressure.	High-quality, uniform coating.	Slow process, requires high temperature.	Semiconductors, microelectronics.
Plasma-Enhanced CVD (PECVD)	Coating process with accelerated chemical reactions using plasma.	Coating at low temperatures, high efficiency.	Plasma control is complex, requires sophisticated equipment.	Microelectronics, optical coatings, medical instruments.
Metal-Organic CVD (MOCVD)	CVD technology using metal-organic precursors.	Very high precision, produces thin coatings.	High cost, requires complex reactors.	Semiconductors, LEDs, optoelectronics.
Hot-Wall CVD	CVD process carried out with heating of reactor walls.	Good heat distribution, easy to achieve uniform coating.	Coating may deposit on reactor walls, slowing the process.	Turbines, corrosion-resistant coatings.
Cold-Wall CVD	CVD process carried out with only the substrate being heated.	Fast coating process, energy-saving.	Difficult to achieve uniform coating.	Hard coatings, microelectronics.

PVD (Physical Vapor Deposition) and CVD (Chemical Vapor Deposition) Coating Methods: A Technological Comparison

Coating Formation Method: In the PVD method, the material is physically evaporated and deposited on the substrate surface. This process is usually carried out in a vacuum environment. In the CVD method, gases undergo a chemical reaction on the surface of the substrate (the base material), forming a solid coating. This process occurs at high temperatures.

Process Temperature: PVD is typically carried out at relatively low to medium temperatures (200–500°C). The CVD method requires high temperatures (600°C and above).

Process Type: In the PVD method, the process is physical, with atoms or molecules of the material being deposited on the substrate surface. In the CVD method, the coating is formed through chemical reactions.

Vacuum and Atmosphere: The PVD method requires a high vacuum. The CVD method can be performed at atmospheric pressure or in a vacuum.

Coating Thickness and Quality Control: Coatings obtained using the PVD method are typically thin and smooth but may encounter difficulties when coating complex shapes. The CVD method allows for the production of thicker coatings and is effective for coating components with complex geometries.

By-products Emitted into the Atmosphere: The PVD method does not produce harmful by-products. In the CVD method, toxic by-products may be generated, requiring additional devices for their removal.

Applications: The PVD method is used for obtaining thin coatings made of metals and ceramic materials, primarily for decorative, wear-resistant, and corrosion-resistant coatings. The CVD method is used for producing high-quality and hard coatings in aviation, microelectronics, optics, and other industries.

3. Conclusion

Increasing the reliability of turbine blades is a critical task that directly impacts the reliability of aviation engines and flight safety. One of the most advanced methods for improving the reliability of blades is the PVD method. The PVD method is environmentally friendly, performed at relatively low temperatures, and allows for coatings of various shapes.

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