SCIENTIFIC AND TECHNICAL EFFICIENCY OF USING METAL-MATRIX NANOCOMPOSITES IN GAS TURBINE ENGINES

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Annotation: This scientific article provides a thorough scientific analysis of the theoretical foundations, material science aspects, design and technological solutions, and operational and economic efficiency of metal matrix nanocomposite (MMNC) materials in modern aviation engines. The micro- and nanostructure of metal matrix nanocomposites, dislocation mechanisms, temperature and mechanical stability, and suitability for operating conditions in aviation engines are covered based on a fundamental approach. The research results show that these materials are of strategic importance in increasing the resource of aviation engines, significantly reducing their weight and fuel consumption, and improving their efficiency.

Keywords: metal matrix nanocomposites, aviation, engines, nanoreinforcements, high-temperature materials.

Аннотация В данной научной статье представлен всесторонний научный анализ теоретических основ, аспектов материаловедения, конструктивных и технологических решений, а также эксплуатационной и экономической эффективности металломатричных нанокомпозитных материалов (ММНК) в современных газтурбинных двигатлях. На основе фундаментального подхода рассмотрены микро- и наноструктура металломатричных нанокомпозитов, механизмы дислокаций, температурная и механическая стабильность, а также пригодность для условий эксплуатации в авиационных двигателях. Результаты исследований показывают, что эти материалы имеют стратегическое значение для увеличения ресурсной базы авиационных двигателей, значительного снижения их веса и расхода топлива, а также повышения их эффективности.

Ключевые слова: металломатричные нанокомпозиты, авиационные, газтурбиных, двигателей, наноармирование, высокотемпературные, материалы.

Annotatsiya. Ushbu ilmiy maqolada zamonaviy aviatsiya dvigatellari — Gazturbinali dvigatellarida metall matritsali nanokompozit (MMNK) materiallarni qo‘llashning nazariy asoslari, materialshunoslik jihatlari, konstruktiv-texnologik yechimlari hamda ekspluatatsion-iqtisodiy samaradorligi chuqur ilmiy tahlil qilinadi. Metall matritsali nanokompozitlarning mikro- va nanostrukturasi, dislokatsiya mexanizmlari, harorat-mexanik barqarorligi hamda aviatsiya gazturbinali dvigatellarida ishlash sharoitiga mosligi fundamental yondashuv asosida yoritilgan. Tadqiqot natijalari ushbu materiallar gazturbinali dvigatellarini resursini oshirish, vaznini sezilarli darajada va yoqilg‘i sarfini kamaytirish hamda samaradorligini yaxshilashda strategik ahamiyatga ega ekanini ko‘rsatadi.

Kalit so‘zlar: metall matritsali nanokompozitlar, aviatsiya, gazturbinali, dvigatellari, nanomustahkamlagichlar, yuqori, haroratli, materiallar.

INTRODUCTION

In the engineering of aviation gas-turbine engines, material selection is a key factor determining the overall efficiency, safety, and economic performance of aircraft. Modern aviation engines operate under extreme conditions—temperatures ranging from 600°C to 1200°C, high rotational speeds, significant centrifugal forces, and cyclic fatigue.

While traditional metal alloys (aluminum, titanium, and nickel-based) are effective up to a certain point, their physical and mechanical capabilities no longer fully meet the demands of modern aviation. In this context, metal-matrix nanocomposites are viewed as materials that usher in a new era in aviation engineering.

Metal-matrix nanocomposites can be utilized in various components of aviation engines:

Components exposed to high temperatures: turbine blades, compressor casings, combustion chambers, and heat-resistant parts;

Components subject to high fatigue and stress: shafts, bearings, and supports.

LITERATURE REVIEW AND RESEARCH METHODOLOGY

The application of metal-matrix nanocomposites in gas turbine engines is linked to opportunities for improving material mass, strength, heat resistance, and operational reliability. Hooker and Doorbar [1] investigated the potential use of aluminum- and titanium-matrix composites in gas turbine aero-engines, demonstrating the capacity of SiC-particle-reinforced aluminum composites to enhance mass and operational efficiency.

Mortensen and Llorca [2] summarized the microstructure, strengthening mechanisms, and mechanical properties of metal-matrix composites, demonstrating that reinforcement with particles and fibers significantly enhances the material's hardness and strength. Modern research focuses on key areas such as the dispersion of nanoscale reinforcements, particle-metal interactions during solidification, and microstructure control. Cao, Killips, and Li [3] conducted a systematic analysis of the fabrication technologies, microstructure, and mechanical and physical properties of MMNC materials. Therefore, evaluating the effectiveness of nanocomposites in gas turbine engines requires a comprehensive study that considers not only mechanical strength but also temperature resistance, mass reduction, and manufacturing feasibility.

The study employs a combination of theoretical-analytical, comparative, and computational-experimental methods. Initially, the literature is analyzed to examine various types of metal-matrix nanocomposites—based on Al, Ti, and other matrices—and the properties of reinforcing nanoparticles such as SiC. Subsequently, the density, specific strength, hardness, thermal stability, and fatigue characteristics of the nanocomposites are compared with those of conventional gas turbine materials. Finally, the mechanical properties of the material and the operational efficiency of structural components are evaluated under high-temperature conditions. Mathematical-statistical analysis, comparative assessment, and multi-criteria efficiency indicators are used to summarize the results. Ultimately, the impact of using nanocomposites on mass reduction, material resources, and the technical efficiency of the gas turbine engine is determined.

ANALYSIS AND RESULTS

Enhancing the performance of key aviation engine components using metal-matrix nanocomposites

Compressor blades and disks operate under high rotational speeds and centrifugal forces. Aluminum- or titanium-based metal-matrix nanocomposites (MMNCs) are used in these components to reduce weight and increase efficiency.

Turbine blades are among the most critical elements of an aviation engine. Nickel-based MMNCs possess the ability to retain strength at high temperatures.

MMNC-based nanocoatings protect turbine components from oxidation and thermal fatigue.

Combustion chamber walls are constantly subjected to high temperatures and chemical exposure. Ceramic-nanophase metal-matrix composites demonstrate high effectiveness in this application. [6]

Manufacturing technologies for metal-matrix nanocomposites:

powder metallurgy;

liquid metal methods;

additive manufacturing (3D printing).

Scientific principles of metal-matrix nanocomposites

Strengthening in metal-matrix nanocomposites occurs through the following primary mechanisms:

Orowan mechanism — nanoparticles impede dislocation movement, thereby increasing strength;

Load transfer effect — a portion of the external load is transferred to the reinforcing phases;

Grain refinement — strength increases in accordance with the Hall-Petch relationship;

Thermal stability — maintenance of structural stability at high temperatures. [2-3].

Suitable metal matrices for aviation

The following matrices are considered superior for aviation engines:

aluminum-based MMCs — lightweight and highly thermally conductive;

titanium-based MMCs — high strength and corrosion resistance;

nickel-based MMCs — for high-temperature turbine components.

Operating conditions and material requirements for gas turbine engines. Gas turbine engines are designed for high power output and long-term operation. Key challenges include:

thermal fatigue effects on turbine blades;

erosion and oxidation of compressor components;

friction and wear in reduction gear assemblies.

Nickel- and titanium-based MMCs are highly effective in addressing these issues [1-5].

Scientific analysis of MMC application in gas turbine engines

Gas turbine engine turbine blades

Nickel-matrix nanocomposites (Ni + Al_2O_3, Ni + Y_2O_3):

mechanical stability at temperatures exceeding 1000°C;

1.3–1.5-fold increase in strength and fatigue resistance;

25–40% extension of operational service life.

Gas turbine engine compressor and shaft assemblies

Titanium-matrix nanocomposites:

reduction of engine weight;

resistance to centrifugal forces;

improved dynamic balance. Turbocharger components

Nickel-based MMNCs:

reduced high-temperature deformation;

enhanced rotational stability.

Operational efficiency and service life analysis

The use of metal matrix nanocomposites results in:

a 20–35% increase in engine service life;

extended maintenance intervals;

improved reliability metrics.

Economic and environmental efficiency

Despite higher production costs, MMNCs offer the following economic benefits:

reduced operating costs;
fuel savings;
reduced CO_2 emissions.

Scientific and technological challenges and solutions

Key challenges:
uniform distribution of nanoparticles;
certification according to aviation standards;
predicting long-term reliability.
Solutions involve advanced powder metallurgy and additive technologies.

Future research directions:

hybrid and electric aviation engines;
functionally graded nanocomposites;
smart (self-healing) materials. [5]

CONCLUSION

Scientific analysis of gas turbine engines indicates that metal-matrix nanocomposites (MMNCs) are materials of strategic importance for aviation engines. Their application enables increased engine efficiency, reduced weight, and extended service life. [1]

Compared to traditional metal alloys, metal-matrix nanocomposites enhance performance and reduce fuel consumption. Scientific and technological research facilitates the expansion of the practical application of these materials. [6]

Metal-matrix nanocomposites are promising materials with significant potential for effective use in aviation engines. Their application substantially improves engine efficiency, reliability, and environmental performance.

MMNCs are expected to become one of the primary structural materials for aviation and aerospace engines in the future.

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