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ADVANCEMENTS IN AEROSPACE ALLOYS: NAVIGATING THE FUTURE OF AVIATION AND SPACE EXPLORATION

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Abstract

In the dynamic world of aerospace engineering, the search for innovative materials has always been at the forefront. The aerospace industry relies heavily on alloys that can withstand extreme conditions, maximize performance, and minimize weight and cost. As we move into the future, several alloys have emerged as the most promising candidates for aerospace applications. Here are a few of the most promising alloys for aerospace applications: composites, nickel-based superalloys, titanium aluminides, high entropy alloys, shape memory alloys, etc. This article provides a brief overview of some of these extraordinary materials that outline a brighter future for the aerospace industry. The article offers a dialogue and cites particular innovations originating from Bulgaria. Future directions for research in this field are explored.

Introduction

Space exploration, along with the design, construction, launch, and operation of spacecraft, relies heavily on advancements in space materials science for the necessary knowledge and application of material properties. The aerospace industry, characterized by its relentless pursuit of innovation and safety, faces unique material requirements and challenges. The harsh operational environments, which include radiation, vacuum, extreme temperatures, high mechanical stresses, and corrosive atmospheres, necessitate materials that not only withstand these conditions but also contribute to the overall efficiency and performance of aerospace vehicles. This has led to an ongoing search for materials that offer the optimal balance between strength, durability, weight, cost, and resistance to environmental factors.

Among the various materials evaluated for aerospace applications, metallic alloys [1–25] stand out due to their exceptional performance characteristics. Alloys, by combining multiple elements, offer enhanced properties that are not attainable with pure metals. This includes improved strength-to-weight ratios, corrosion resistance, greater resistance to radiation, and high-temperature stability, which are critical for the structural and engine components of aircraft and spacecraft. The development of alloys tailored for aerospace applications has been a pivotal factor in the advancement of the industry, enabling the realization of faster, lighter, and more efficient vehicles.

The purpose of this article is to explore the panorama of alloys in the aerospace industry, highlighting those that have shown the greatest promise in meeting the stringent demands of the sector [1–9]. We aim to provide an overview of the current state of alloy development and application in aerospace, detailing the properties that make these materials stand out and the challenges that come with their use. Additionally, the scope of the article will include an examination of the innovations in alloy composition and processing techniques that are driving the next generation of aerospace materials. Some Bulgarian developments in the field of aerospace alloys are also mentioned.

Some historical perspective

The aerospace industry's evolution is marked by significant advancements in materials, from early 20th-century aluminium usage to the recent development of high-entropy alloys (HEAs). Initially, aluminium revolutionized aircraft design with its favorable strength-to-weight ratio, leading to the era of metal planes and subsequent innovations in materials science. The need for materials to meet the demanding conditions of flight and space exploration spurred the development of alloys like duralumin and titanium alloys. Titanium, introduced in the 1950s, and nickel-based superalloys, designed for their high-temperature strength, have been crucial in aviation and space research, enabling lighter, stronger components and efficient propulsion systems.

Table 1. Materials (as percentage of weight) used in Boeing series aircraft and Airbus A350

Airplane model	*Year of commissioning*	*The total materials used in aircraft in wt %*				
		Al alloys	*Steels*	*Ti alloys*	*Composites*	*Others*
747	*1970*	*81*	*13*	*4*	*11*	*1*
767	*1982*	*80*	*14*	*2*	*3*	*1*
777	*1995*	*70*	*11*	*7*	*11*	*1*
787 (Dreamliner)	*2011*	*20*	*10*	*15*	*50*	*5*
A350 XWB	*2015*	*19*	*6*	*14*	*53*	*8*

The commonly used materials in the aerospace field include Al alloys, steels, titanium (Ti) alloys, and composites. Table 1 [3,10] shows the total materials used in Boeing series aircraft and Airbus A350. Al-based alloys tend to decrease, and composites have experienced a rapid increase in the total materials in the latest Boeing and Airbus models. Over the past two decades, the trend observed in Boeing and Airbus models (refer to Table 1) highlights a broader shift within the aerospace industry towards the adoption of composite materials and Metal Matrix Composites (MMCs) [3, 11]. This transition away from traditional aluminium (Al) alloys is universally recognized across various aerospace vehicles, with variations in percentage ratios depending on the model and its specific application. The shift towards composites and MMCs has yielded significant benefits, including enhanced strength-to-weight ratios and mechanical properties tailored for aerospace applications. Quantifying the exact percentage ratio of these materials' usage in the aerospace industry requires specific data from aerospace manufacturers and depends on the types of aircraft or spacecraft being produced, which is constantly evolving with the development of new materials and technologies.

The introduction of HEAs [9] at the start of the 21st century, with their unique multi-component composition, represents a paradigm shift in materials science, promising materials with enhanced strength and resistance to extreme conditions. This historical progression from basic materials to advanced alloys and composites underlines the aerospace industry's continuous innovation, driving the transition from the first powered flights to modern aerospace engineering and beyond.

Principal features of aerospace materials

The selection of materials for aerospace applications depends on a comprehensive set of criteria aimed at providing optimal performance, durability, and performance under extreme operating conditions. Specifically, aerospace alloys are evaluated based on their:

Mechanical properties: This includes the material's strength, which measures its resistance to deformation under load; fatigue resistance, indicating its ability to withstand repeated stress cycles without failing; and hardness, reflecting its resistance to surface deformation or indentation. These properties are critical for the structural integrity and reliability of aerospace components, which are subject to rigorous operational demands.

Thermal properties: Important thermal characteristics include high-temperature resistance, which ensures material stability and performance at the elevated temperatures encountered in engine compartments and during atmospheric re-entry, and thermal conductivity, which affects the material's ability to conduct heat. Effective management of thermal properties is essential for maintaining operational integrity and preventing material failure due to thermal stresses.

Corrosion resistance and durability: The durability of aerospace alloys, significantly influenced by their corrosion resistance, ensures long-term reliability and structural integrity. Materials used in aerospace must withstand various corrosive environments, from salty ocean air to the chemical exposures in space. Alloys with high corrosion resistance demand less frequent maintenance and replacement, contributing to the longevity and cost-effectiveness of aerospace projects.

Weight and Density: In aerospace engineering, minimizing weight without compromising strength or performance is paramount. Low-density but high-strength materials contribute to fuel efficiency and payload optimization. The trade-off between weight and mechanical properties is a key consideration in the design and selection of aerospace alloys.

Radiation Resistance: For space applications, radiation resistance is a paramount characteristic, protecting spacecraft components and occupants from the harmful effects of cosmic radiation and solar particles. Materials that can effectively shield against or withstand radiation exposure without significant degradation are essential for the safety and success of space missions. The development of alloys with enhanced radiation resistance is crucial for advancing space exploration and long-duration missions beyond Earth's orbit, ensuring mission success and safety.

Outline of some prominent aerospace alloys

A variety of alloys have been developed and utilized in aerospace applications, each offering unique properties and performance characteristics to cater to specific needs. In this section, we will conduct a review of commonly used alloys in the aerospace industry, providing an analysis of their properties and performance (see also Table 2).

Nickel-based superalloys

Nickel-based superalloys [5] play a crucial role in modern technology, enabling advancements and efficiencies in several critical sectors. Their unique combination of high-temperature capability, strength, and corrosion resistance underpins the performance and reliability of systems and components operating under the most demanding conditions. Nickel-based superalloys are integral to the aerospace industry, offering unmatched performance in high-temperature, high-stress environments typical of jet engine and turbine applications. As materials science continues to evolve, the development of new superalloys with enhanced properties is expected to further expand their applications and significance in the future.

Several grades of these superalloys have been developed over the years, each tailored for specific requirements. Here are some notable examples:

Inconel 718

Applications: Inconel 718 is perhaps the most widely used Nickel-based superalloy in aerospace engineering. It is employed in various engine components, including turbine disks, compressor blades, casings, and fasteners. Its popularity stems from its exceptional combination of strength, corrosion resistance, and ability to withstand high temperatures up to about 700°C (1292°F).

Rene 41

Applications: Rene 41 is utilized in high-temperature turbine blades, disks, and other engine components that require high strength and resistance to creep up to temperatures of around 760°C (1400°F). Its excellent mechanical properties at high temperatures make it a preferred choice for critical aerospace components.

Waspaloy

Applications: Waspaloy finds its use in turbine disks and shafts, as well as in other engine parts subjected to high temperatures. It is known for its high strength and good resistance to oxidation and corrosion at temperatures up to approximately 870°C (1600°F).

Hastelloy X

Applications: Although not exclusively a Nickel-based superalloy (as it includes significant amounts of other elements like chromium), Hastelloy X is notable for its application in gas turbine engine combustion zones, including combustor cans and transition ducts. It can withstand temperatures up to about 1200°C (2192°F) and is valued for its oxidation resistance.

Mar-M 247

Applications: Mar-M 247 is particularly suited for casting turbine blades and vanes due to its excellent creep and fatigue resistance at high temperatures. It is commonly used in high-pressure turbine sections where the material is exposed to extreme thermal cycles and stresses.

CMSX-4 (Single Crystal Superalloy)

Applications: CMSX-4 is a single-crystal Nickel-based superalloy used in turbine blades and vanes for its exceptional high-temperature performance. The absence of grain boundaries in the single-crystal structure offers superior creep resistance and strength at temperatures exceeding 1100°C (2012°F), significantly improving the efficiency of modern jet engines.

These examples illustrate the diversity and specialization within the range of Nickel-based superalloys used in aerospace applications. Each grade offers a unique set of properties designed to meet specific operational challenges, contributing to the advancements in efficiency, reliability, and performance of aerospace propulsion systems. The continuous development of these materials reflects the ongoing pursuit of higher performance and durability in the aerospace industry.

Titanium alloys

Titanium and titanium alloys [5, 7] are also widely used in the aerospace industry due to their excellent properties. Titanium has an excellent strength-to-weight ratio, corrosion resistance, and ability to withstand high temperatures. Titanium behaves extremely well in the extreme conditions of outer space, meaning that titanium is a huge asset in advancing space exploration. These alloys are critical for high-performance applications such as jet engine components, airframes, and spacecraft structures, where durability and weight reduction are paramount. Here are some specific grades of titanium alloys and their aerospace applications:

Ti-6Al-4V (Grade 5)

This is arguably the most commonly used titanium alloy in aerospace engineering. It consists of 6% aluminium, 4% vanadium, and the remainder titanium. Its applications in aerospace are vast due to its high strength, light weight, and excellent corrosion resistance. It is used in: Aircraft structures and frames; Engine components (compressor blades, disks); Fasteners and landing gear parts.

Ti-6Al-2Sn-4Zr-2Mo (Grade 5)

This alloy is known for its high strength at elevated temperatures, making it suitable for high-temperature aerospace applications. Its uses include: Jet engine parts, particularly in hot sections; Airframe components subjected to high temperatures.

Ti-3Al-2.5V (Grade 9)

This grade is slightly lower in strength compared to Ti-6Al-4V but offers better weldability and cold formability. It is often used in: Hydraulic tubing; Structural components where welding is required; Bicycle frames (non-aerospace but showcases its versatility).

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Beta C or Ti-17)

A beta alloy known for its high strength and good resistance to creep up to 600°C. Its aerospace applications include: High-strength fasteners; Aircraft landing gear; Structural components in high-temperature zones.

Ti-6Al-2Sn-4Zr-6Mo

This alloy is noted for its high strength and good toughness. It's used in areas where high strength is required at temperatures up to 450°C, such as Engine components, Airframes, and High-performance fasteners.

Ti-15V-3Cr-3Sn-3Al

A cold-formable beta alloy used for applications requiring high strength-to-weight ratios and corrosion resistance at ambient to moderately elevated temperatures. Applications include: Airframe skins; Actuators; Structural components where formability is critical.

Ti-6Al-4V ELI (Extra Low Interstitial, Grade 23)

A version of Ti-6Al-4V with lower oxygen, nitrogen, and carbon content, offering improved ductility and fracture toughness. It's especially used in: Medical implants (non-aerospace); Aerospace applications where improved toughness is required.

Titanium aluminides

Titanium aluminides [8] are intermetallic compounds composed primarily of titanium and aluminium, often with small additions of other elements to enhance specific properties. They offer a unique combination of high strength, low density, and excellent high-temperature properties, making them attractive for aerospace applications, particularly in aircraft engines and airframes. Here are some specific examples of titanium aluminide grades with aerospace applications:

Ti-48Al-2Cr-2Nb (Gamma TiAl): This alloy, also known as gamma titanium aluminide, is one of the most widely studied and used titanium aluminides in aerospace applications. It consists of titanium (Ti), aluminium (Al), chromium (Cr), and niobium (Nb). Gamma TiAl offers a high strength-to-weight ratio, excellent high-temperature stability, and good oxidation resistance, making it suitable for components in aircraft engines, such as turbine blades and vanes.

Ti-48Al-2Cr-2Nb (Orthorhombic TiAl): Orthorhombic titanium aluminide is another variant of Ti-48Al-2Cr-2Nb, distinguished by its crystal structure. It exhibits improved fracture toughness compared to gamma TiAl and is particularly suitable for applications where impact resistance is critical, such as airframe structural components and landing gear parts.

Ti-24Al-11Nb (Alpha-2 TiAl): Alpha-2 titanium aluminide contains titanium (Ti), aluminium (Al), and niobium (Nb). It offers a balance of high-temperature strength, creep resistance, and low thermal expansion, making it suitable for use in aircraft engine components subjected to elevated temperatures, such as exhaust systems, and hot-section parts.

Ti-6Al-2Sn-4Zr-2Mo (Ti-6242): This titanium aluminide alloy contains titanium (Ti), aluminium (Al), tin (Sn), zirconium (Zr), and molybdenum (Mo). While it includes more traditional alloying elements compared to other titanium aluminides, it still exhibits many of the desirable properties, including high strength, light weight, and good high-temperature performance. Ti-6242 is used in aerospace applications, including aircraft engine components and structural parts requiring high strength and fatigue resistance.

Ti-22Al-25Nb (TNM-B1): This titanium aluminide alloy contains titanium (Ti), aluminium (Al), and niobium (Nb). It offers a combination of high-temperature strength, low density, and good oxidation resistance, making it suitable for aerospace applications, including turbine components in jet engines and structural components in aircraft airframes.

These examples demonstrate the variety of titanium aluminide grades used in aerospace applications, each tailored to meet specific requirements such as high-temperature performance, strength, and lightweight design. Ongoing research continues to explore new alloy compositions and processing techniques to further enhance the properties and suitability of titanium aluminides for aerospace use.

Aluminium alloys

Aluminium alloys [10, 12–20] are currently the most commonly used metals in the aerospace industry, but certainly not the only ones. Proof of this is the vast amount of literature available on aluminium alloys. Aluminium alloys are renowned for their lightweight, excellent corrosion resistance, and good mechanical properties. Reinforced with various elements such as copper, magnesium, and zinc, these alloys achieve a fine balance between strength and ductility, making them indispensable in aircraft, fuselage, and wing structures. The various aluminium series illustrate the versatility of aerospace aluminium alloys, offering customized properties for different applications. The high strength-to-weight ratio of aluminium alloys makes them ideal for reducing overall weight and improving fuel efficiency in aircraft. Some specific examples of aluminium alloy grades commonly used in aerospace applications include:

2024-T3: This high-strength alloy is widely used in aircraft structural components, such as wings, fuselages, and landing gear. It offers excellent fatigue resistance and is easy to weld and machine.

7075-T6: Known for its high strength-to-weight ratio, 7075-T6 is used in the construction of aircraft structures, including airframes and wing spars. It is also commonly used in aerospace components requiring high strength and stress resistance.

6061-T6: This versatile alloy is used in a variety of aerospace applications, including aircraft parts, landing gear components, and avionics enclosures. It offers good corrosion resistance and is easily weldable.

7050-T7451: This alloy is known for its high toughness and resistance to stress corrosion cracking. It is used in aircraft wing skins, fuselage frames, and other critical structural components.

5083-H321: This alloy is commonly used in marine and aerospace applications, where high corrosion resistance and weldability are important. It is often used in the construction of aircraft fuel tanks and other components requiring resistance to seawater corrosion.

These are just a few examples of the many aluminium alloy grades used in aerospace applications, each chosen for its specific properties and performance characteristics that make it suitable for the demanding requirements of the aerospace industry.

Metal matrix composites

Metal Matrix Composites (MMCs) [3, 11] are engineered materials consisting of a metal matrix reinforced with one or more secondary phases, such as ceramic particles, fibers, or whiskers. They offer enhanced mechanical properties, including high strength, stiffness, and wear resistance, making them suitable for various aerospace applications. Here are some specific examples of Metal Matrix Composites grades with aerospace applications:

Aluminium Matrix Composites (AMCs):

Al-SiCp (Aluminium-Silicon Carbide Particulate): AMCs reinforced with silicon carbide (SiC) particles are commonly used in aerospace applications due to their high strength-to-weight ratio, excellent wear resistance, and thermal stability. They are utilized in components such as rocket nozzles, satellite structures, and aircraft engine parts.

Al-Cu-Mg/SiC (Aluminium-Copper-Magnesium/Silicon Carbide): These composites incorporate copper (Cu), magnesium (Mg), and silicon carbide (SiC) particles in an aluminium matrix. They offer improved mechanical properties and wear resistance, making them suitable for aerospace applications, including aircraft structural components, engine parts, and thermal management systems.

Titanium Matrix Composites (TMCs):

Ti-MMCs (Titanium Matrix Composites): TMCs consist of a titanium (Ti) matrix reinforced with ceramic particles like titanium diboride (TiB_2) or titanium carbide (TiC). They offer increased strength, stiffness, and high-temperature performance compared to pure titanium. TMCs are used in aerospace components such as engine parts, airframe structures, and landing gear.

Ti-MMCs with Carbon Nanotubes (CNTs): Titanium matrix composites reinforced with carbon nanotubes exhibit improved mechanical properties, including enhanced tensile strength and fatigue resistance. They find applications in aerospace systems requiring lightweight materials with superior performance, such as spacecraft components and advanced propulsion systems.

Magnesium Matrix Composites (MMCs):

Mg-Al/SiC (Magnesium-Aluminium/Silicon Carbide): MMCs consisting of magnesium (Mg) matrix reinforced with aluminium (Al) and silicon carbide (SiC) particles offer improved strength, stiffness, and corrosion resistance compared to pure magnesium. They are used in aerospace applications such as lightweight structural components, aircraft frames, and engine parts.

These examples illustrate the versatility and potential of Metal Matrix Composites in aerospace applications, offering tailored solutions to meet the demanding requirements of modern aircraft and spacecraft components. Continued research and development in MMCs aim to further enhance performance, reduce costs, and expand their use in the aerospace industry.

High entropy alloys

High Entropy Alloys (HEAs) [9] are a novel and promising class of materials with potential applications in aerospace engineering, offering unique properties such as high strength, excellent temperature resistance, and superior corrosion resistance. Although the application of HEAs in aerospace is still in the research and experimental stages, some specific alloys have demonstrated potential for use in the aerospace sector.

CoCrFeNiAl: This alloy consists of cobalt (Co), chromium (Cr), iron (Fe), nickel (Ni), and aluminium (Al). It exhibits excellent high-temperature oxidation resistance and mechanical properties, making it suitable for aerospace turbine engine components like turbine blades and combustor liners.

AlCoCrFeNiTi: This alloy includes aluminium (Al), cobalt (Co), chromium (Cr), iron (Fe), nickel (Ni), and titanium (Ti). It has been studied for its potential in aerospace applications, particularly in aircraft engine components and structural materials due to its high strength, oxidation resistance, and thermal stability.

AlCrCuFeNi2: Comprising aluminium (Al), chromium (Cr), copper (Cu), iron (Fe), and nickel (Ni), this HEA demonstrates promising properties for aerospace applications, including high strength, good thermal stability, and resistance to oxidation and corrosion. It could be utilized in aircraft structural components and engine parts.

CoCrCuFeNi: This alloy combines cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), and nickel (Ni). Its excellent mechanical properties, including high strength and hardness, make it suitable for aerospace applications such as aircraft engine components and structural materials requiring enhanced performance under extreme conditions.

FeMnNiCoCr: This HEA consists of iron (Fe), manganese (Mn), nickel (Ni), cobalt (Co), and chromium (Cr). Its unique combination of elements offers good strength, ductility, and corrosion resistance, making it a potential candidate for aerospace structural components and coatings.

Shape memory alloys

Shape memory alloys (SMAs) [6] are a unique class of metal alloys that have the ability to return to a predetermined shape when heated above a certain temperature. This unique property makes SMAs ideal for a variety of aerospace applications where precise control of materials is required. Here are some specific examples of SMA grades and their aerospace applications:

Nitinol (Nickel-Titanium)

Actuators and Damping Systems: Utilized in satellite antennas and solar array positioning systems for their reliable actuation capabilities without the need for external power sources.

Morphing Structures: Used in wing flaps and other aerodynamic surfaces to adjust shape in-flight for optimal performance and fuel efficiency.

Cu-Al-Ni (Copper-Aluminium-Nickel)

Temperature Control Systems: Employed in temperature-sensitive actuators that can automatically adjust cooling louvers or regulate environmental control systems in aircraft without the need for electronic controls.

Vibration Damping: Used in helicopter rotor blades to reduce vibration and enhance passenger comfort and structural integrity.

Cu-Zn-Al (Copper-Zinc-Aluminium)

Safety Devices: Incorporated into locking mechanisms for emergency exit doors, ensuring they operate correctly in response to temperature changes.

Thermal Protection Systems: Applied in spacecraft for components that require passive thermal management during re-entry or exposure to the sun.

Fe-Mn-Si (Iron-Manganese-Silicon)

Self-Healing Structures: Explored for use in critical structural components that can "heal" or revert to their original shape after experiencing deformations, potentially increasing safety and reducing maintenance.

Ni-Ti-Pd (Nickel-Titanium-Palladium)

High-Temperature Actuators: Developed for applications requiring SMAs to operate at higher temperatures, such as in engine components or near hot sections of aircraft, where traditional Nitinol's phase transformation temperatures would not be sufficient.

Shape memory alloys offer transformative potential for aerospace applications, from improving aerodynamic efficiency and passenger comfort to enhancing safety and reducing reliance on traditional mechanical systems. As research and development in SMAs continue, their applications in aerospace are expected to expand, offering innovative solutions to complex engineering challenges.

Table 2. Comparative analysis of the advantages and disadvantages of some alloys

Alloys	*Advantages*	*Disadvantages*
Nickel-Based Superalloys	*Superior mechanical properties; High-temperature strength; Excellent corrosion resistance*	*High cost; Limited formability*
Titanium-Based Alloys	*Exceptional strength-to-weight ratio; Corrosion resistance; High-temperature stability*	*High cost of production; Limited availability of raw materials*
Aluminium Alloys	*Lightweight; Good corrosion resistance; Cost-effective; Strength-to-weight ratio*	*Lower strength compared to titanium and nickel alloys; Susceptible to fatigue failure under cyclic loading; Not suited for high-temperature applications*
Titanium Aluminides	*Lightweight; High-temperature strength; Good oxidation resistance*	*Brittle at low temperatures; Limited ductility*
Metal Matrix Composites (MMCs)	*High stiffness and strength; Tailored properties; Excellent thermal stability*	*High manufacturing costs; Susceptibility to matrix cracking*
Shape Memory Alloys (SMAs)	*Adaptive capabilities; Shape memory effect; Damping properties*	*Limited recovery strain; Sensitivity to temperature uctuations*
High Entropy Alloys	*Unique microstructures; High strength and ductility;*	*Limited understanding of long-term performance;*

(HEAs)	*Potential for lightweight applications*	*Challenges in processing and fabrication*
Functionally Graded Materials (FGMs) [4,22-25]	*Tailored properties; Reduced stress concentrations; Improved performance under thermal gradients*	*Complexity in design and fabrication; Limited understanding of long-term behavior*
Composite Alloys	*High strength-to-weight ratio; Tailored properties; Enhanced fatigue resistance*	*Complexity of manufacturing processes; Limited repairability*

Innovations in alloy development

Alloy innovations (advanced materials engineering, additive manufacturing, sustainable materials development, multifunctional alloys, nanomaterials and nanostructuring, tailored properties for specific applications) [3–5, 20–23] are essential in advancing aerospace materials, with research aimed at new manufacturing methods, surface treatments, and coatings to improve properties and resilience under conditions like high temperatures, corrosion, and radiation. Advancements in additive manufacturing (AM) and powder metallurgy are creating complex structures with enhanced performance, while innovative surface treatments and coatings aim to increase wear and corrosion resistance, thereby extending the lifespan of components. Research is also concentrated on developing alloys with greater thermal stability, corrosion resistance, and radiation tolerance, crucial for enduring extreme environments. Ultimately, the progress and collaboration in alloy research are key to unlocking their full potential in aerospace applications.

Future missions and projects relying on advanced alloys

Future space missions will rely heavily on advanced alloys for next-generation applications that will play a key role in the following key areas:

<u>Space Exploration and Colonization:</u> Missions to the Moon, Mars, and beyond need materials like nickel-based superalloys and titanium alloys for spacecraft and habitats to withstand the harsh conditions of space.

<u>Hypersonic Flight and Space Tourism:</u> Materials that can endure extreme temperatures and forces, such as nickel-based superalloys and ceramic matrix composites, are essential for hypersonic aircraft and spaceplanes, promoting space access and tourism.

<u>UAVs and Drones:</u> Lightweight, high-strength advanced alloys are crucial for UAVs and drones, supporting advanced payloads and enhancing performance.

<u>Sustainable Aviation and Green Technologies:</u> Advanced alloys, including aluminium-lithium alloys, help reduce fuel consumption and emissions in aviation, contributing to sustainability.

The future of aerospace depends on continued advancement in alloys to meet the sector's evolving demands, enabling new exploration and technologies.

Sustainability and recycling for materials in the aerospace industry

The aerospace industry emphasizes environmental sustainability, prioritizing renewable resources like aluminium and titanium [11, 20] and selecting energy-efficient alloys to decrease carbon emissions. Lifecycle assessments and lightweight alloys are used to enhance fuel efficiency. Advanced recycling and circular economy principles are key to preserving the integrity of valuable alloys, with methods like vacuum melting to reduce impurities. Efforts towards closed-loop recycling, remanufacturing, and simplified disassembly aim to extend material lifespan and lower the industry's environmental impact. Cross-sectoral reuse of aerospace alloys in automotive and construction further boosts sustainability. Collaborative work between manufacturers, recyclers, and regulators is crucial for improving recycling processes and sustainable practices, crucial for reducing the aerospace sector's ecological footprint and advancing towards sustainability.

Bulgarian contribution to aerospace alloys

In our Space Materials Science department at the Space Research and Technology Institute (SRTI), a new Al-based composite was synthesized, utilizing the aluminium alloy 7075 (also known as B95), which was strengthened with nanoparticles of nanodiamond powder (ND) and tungsten (W). These detonation nanodiamonds were employed as reinforcing particles to enhance the mechanical properties of the aluminium alloy. Samples of this enhanced B95+W+ND alloy were integrated into the block DP-PM for the "Obstanovka 1-step" international space experiment on the International Space Station (ISS), a collaboration involving England, Bulgaria, Poland, Russia, Ukraine, and the Czech Republic [15]. The experiment sought to investigate the effects of the space environment on the alloy's properties over a span of 28 months. Upon their return to Earth, the analysis of the samples showed an increased hardness in those exposed to space conditions compared to the reference samples [16]. This augmentation is ascribed to radiation-induced defects and temperature cycles that refined the material's structure [17]. This finding demonstrates the potential of space exposure to significantly enhance the mechanical properties of alloys.

In addition, in our department at SRTI-BAS, we have experience in studying the structural and physico-mechanical properties of nano-microcrystalline ribbons of aluminium alloys, obtained by rapid solidification from the melt. These Al alloys, from the Al-Si system, are designed to replace Ti alloys in high-temperature applications [18].

At SRTI, we are also advancing research on new functionally graded materials (FGMs) that utilize reinforced aluminium metal matrix composites.

These materials are poised to attract significant interest due to their potential applications in space technology, particularly in aerospace instrumentation. Research in this area is actively ongoing [22–23].

Conclusions

In conclusion, the aerospace industry has evolved significantly over the past two decades, shifting from traditional aluminium alloys to advanced materials like composites, Metal Matrix Composites (MMCs), and high entropy alloys. This evolution, driven by material scientists and engineers' ingenuity and interdisciplinary collaboration, is crucial for developing more efficient and sustainable aerospace vehicles. The importance of these advanced materials, including nickel-based superalloys and shape memory alloys, is underscored by their ability to meet the demands of space exploration and aviation through improved performance attributes.

Significant contributions, notably from Bulgarian research into Al-based composites and nano-microcrystalline aluminium alloys, highlight the global collaborative effort in aerospace material innovation. The "Obstanovka 1-step" space experiment's results, demonstrating enhanced mechanical properties from space exposure, suggest new possibilities for aerospace material applications.

As the industry approaches a new era focused on sustainable innovation, the role of advanced aerospace alloys becomes increasingly pivotal. This journey from aluminium to complex, high-performance materials reflects not just advancements in aerospace engineering but also the broader progress of human exploration and innovation. The continued development and optimization of these materials are central to navigating the challenges of future aerospace endeavors.

References

1. Zhang, X., Y. Chen, J. Hu, Recent advances in the development of aerospace materials Progress in aerospace sciences, 2018, 97, 22–34, https://doi.org/10.1016/j.paerosci.2018.01.001
2. Soni, R., R. Verma, R. K. Garg, V. Sharma, A critical review of recent advances in the aerospace materials, Materials Today: Proceedings, 2023, https://doi.org/10.1016/j.matpr.2023.08.108
3. Bachmann, J., C. Hidalgo, S. Bricout, Environmental analysis of innovative sustainable composites with potential use in aviation sector–A life cycle assessment review, Science China Technological Sciences, 2017,60(9), 1301–1317, doi: 10.1007/s11431-016-9094-y
4. Bharti, I., N. Gupta, K. M. Gupta, Novel Applications of Functionally Graded Nano, Optoelectronic and thermoelectric materials, Int. J. of Materials, Mechanics and Manufacturing, 2013, 1, 221–224

5. Madigana, C. S., A. Vaddula, S. D. Yerramsetti, K. M. Buddaraju, Additive manufacturing of titanium and nickel-based superalloys: A review, Materials Today: Proceedings, 2023 (in press), https://doi.org/10.1016/j.matpr.2023.07.082
6. Costanza, G., M. E. Tata, Shape memory alloys for aerospace, recent developments, and new applications: A short review, Materials, 2020, 13(8), 1856, https://doi.org/ 10.3390/ma13081856
7. Williams, J. C., R. R. Boyer, Opportunities and issues in the application of titanium alloys for aerospace components, Metals, 2020, 10(6), 705, https://doi.org/10.3390/ met10060705
8. Clemens, H., S. Mayer, Intermetallic titanium aluminides in aerospace applications - processing, microstructure and properties, Materials at high temperatures, 2016, 33(4–5), 560–570, http://dx.doi.org/10.1080/09603409.2016.1163792
9. Dada, M., P. Popoola, N. Mathe, Recent advances of high entropy alloys for aerospace applications: a review, World Journal of Engineering, 2023, 20(1), 43–74, https://doi.org/10.1108/WJE-01-2021-0040
10. Warren, A. S., Developments and challenges for aluminum--A Boeing perspective, Materials forum, 2004, 28, 24–31
11. Nagaraju, S. B., H. C. Priya, Y. G. T. Girijappa, M. Puttegowda, Lightweight and sustainable materials for aerospace applications, In Lightweight and Sustainable Composite Materials, 2023, Woodhead Publishing, 157–178, https://doi.org/ 10.1016/B978-0-323-95189-0.00007-X
12. Li, S. S., X. Yue, Q. Y. Li et al., Development and applications of aluminum alloys for aerospace industry, Journal of Materials Research and Technology, 2023, 27, 944–983, https://doi.org/10.1016/j.jmrt.2023.09.274
13. Gloria, A., R. Montanari, M. Richetta, A. Varone, Alloys for aeronautic applications: State of the art and perspectives, Metals, 2019, 9(6), 662, https://doi.org/ 10.3390/met9060662
14. Dursun, T., C. Soutis, Recent developments in advanced aircraft aluminium alloys, Materials & Design (1980–2015), 56, 862–871, https://doi.org/10.1016/ j.matdes.2013.12.002
15. Bouzekova-Penkova A., S. Klimov, V. Grushin et al., Space Experiment "Obstanovka (1 - stage)", block DP - PM of the Russian segment of the International Space Station (ISS), Aerospace Research in Bulgaria, 2023, 35; 156–164, https://doi.org/10.3897/ arb.v35.e15
16. Bouzekova-Penkova A., M. Datcheva, R. Iankov, Mechanical properties of the enhanced with nanodiamond and tungsten strengthened aluminium alloy being exposed in the Outer space, International Journal “NDT Days”, 2019, II, 4, 396–401, 10.5281/zenodo.3548122
17. Bouzekova-Penkova A., S. Simeonova, R. Dimitrova, R. Dimitrova, Structural properties of aluminium alloy enhanced by nanodiamond and tungsten exposed in the outer space, Comptes rendus de l’Acade'mie bulgare des Sciences, 2020, 73(9), 1270–1276, 10.7546/CRABS.2020.09.11
18. Petrova, A., G. Stefanov, A. Miteva, Some properties of the nanozone in nano-microcrystalline ribbons of aluminium alloys, Comptes rendus de l Academie bulgare des Sciences, 2020, 73(10), 1434–1442, 10.7546/CRABS.2020.10.13

19. Bouzekova-Penkova, A., A. Miteva, Some aerospace applications of 7075 (B95) aluminium alloy, Aerospace Research in Bulgaria, 2022, 34, 165–179, https://doi.org/10.3897/arb.v34.e15
20. Aboukhatwa, M., D. Weiss, Upcycling of aerospace aluminum scrap, Technology innovation for the circular economy: recycling, remanufacturing, design, systems analysis and logistics, 2024, 343–354, https://doi.org/10.1002/9781394214297.ch27
21. Blakey-Milner, B., P. Gradl, G. Snedden et al., Metal additive manufacturing in aerospace: A review, Materials & Design, 2021, 209, 110008, https://doi.org/10.1016/j.matdes.2021.110008
22. Miteva, A., A. Bouzekova-Penkova, Some aerospace applications of functionally graded materials, Aerospace Research in Bulgaria, 2021, 33, 195–209, https://doi.org/10.3897/arb.v33.e14
23. Bouzekova-Penkova, A., A. Miteva, Aluminium-based functionally graded materials, In Bulgarian Academy of Sciences, 2014, vol. 10
24. Miyamoto, Y., W. A. Kaysser, B. H. Rabin, A. Kawasaki, R. G. Ford (Eds.), Functionally graded materials: design, processing and applications, Vol. 5, Springer Science & Business Media, 2013, 339
25. Mahamood, R. M.and E. T. Akinlabi, Functionally graded materials. Topics in mining, metallurgy and materials engineering, Springer, Cham, 2017, 103

НАПРЕДЪК В ОБЛАСТТА НА АЕРОКОСМИЧЕСКИТЕ СПЛАВИ: НАВИГАЦИЯ В БЪДЕЩЕТО НА АВИАЦИЯТА И КОСМИЧЕСКИТЕ ИЗСЛЕДВАНИЯ

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Резюме

В динамичния свят на аерокосмическото инженерство непрекъснатото търсене на иновативни материали е ключов приоритет. Аерокосмическата индустрия се нуждае от сплави, които издържат на екстремни условия и оптимизират производителността и ефективността, като едновременно с това намаляват теглото. Сред многото изследвани материали, няколко сплави изпъкват като особено перспективни за аерокосмически приложения, включи-телно никелови огнеустойчиви сплави, титанови алуминиди, сплави с висока ентропия и сплави с памет на формата. Тази статия очертава бъдещето на аерокосмическата индустрия чрез анализ на тези новаторски материали и подчертава приноса на българските иновации в областта. Също така се разглеждат бъдещите насоки за изследване, които могат да допринесат за развитието на аерокосмическата наука и технология.