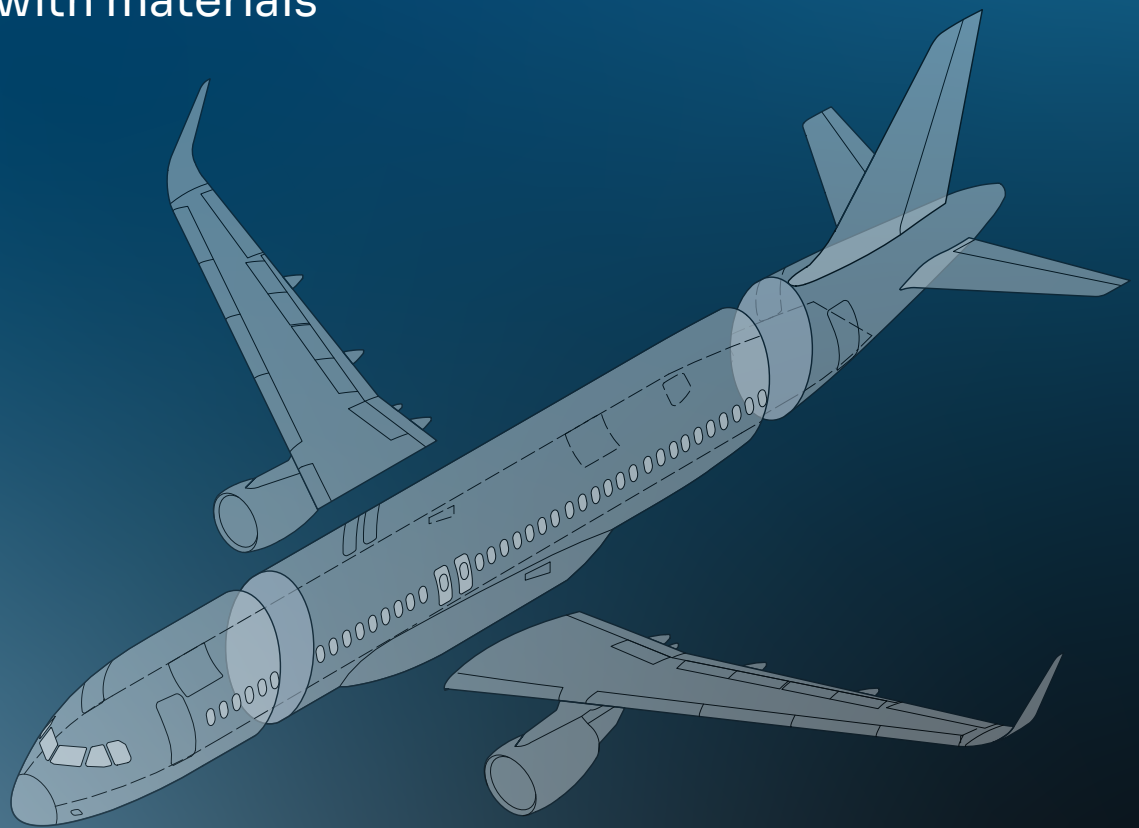


**FUTURE  
STARTS  
ABOVE**



# Materials Matter

Technological sovereignty  
begins with materials



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## Opening notes



The German aerospace industry is one of the most technologically advanced and innovative sectors of the economy in our country. Its international competitiveness largely stems from its ongoing development of existing technologies and its systematic exploration of new fields of research. In this context, materials development plays a crucial role: It lays the groundwork for future aircraft and spacecraft designs and significantly contributes to the achievement of ambitious technological, environmental, and economic goals.

Developing new materials requires long-term, strategic approaches. From the initial concept to industrial-scale technological maturity, developing a new material can take significantly longer than developing a traditional product – timeframes of up to 20 years are not uncommon. A key challenge is that materials development must precede product development. Before the development of an actual product can begin, a new material must reach industrial maturity.

This necessitates a forward-looking, long-term materials strategy, in which future product development requirements are anticipated and evaluated at an early stage. Such a strategy can only be successfully implemented through collaboration between all relevant stakeholders, including universities, non-university research institutions, and industrial end users throughout the entire supply chain.

In light of global market shifts, growing geopolitical uncertainty, and the increasing demand for sustainability and resource efficiency, it is of crucial importance that we strategically secure high-performance materials within national and European supply chains.

Future materials research must adopt a more strategic approach, considering not only the classic requirements of thermo-mechanical properties but also the entire value chain. In addition to material performance alone, the long-term availability of raw materials and ecological, social, and geopolitical conditions must be systematically considered.



**AIRBUS**



**Leistritz**



**Novelis**



**TEIJIN CARBON**



Significant parts of the materials supply chains for users in Germany and Europe are located outside the continent, making them vulnerable to potential dependencies and risks. The groundwork for overcoming these challenges is laid as early as the materials development stage. Both the selection of alloys and functional elements and the associated manufacturing and processing procedures play a key role in determining the sustainability, resilience, and strategic robustness of a materials concept.

In approaching this, the German aerospace industry is supported by an excellent research landscape consisting of leading scientific institutions, universities, independent research institutions, and industrial innovation partners.

Past research activities have yielded significant progress, particularly through the development of new materials and processes, such as sustainable metal fuselage technologies for the next generation of single-aisle programs and technologies for the industrial-scale production of composite wings and additive manufacturing processes, which are now being used more frequently. Federal funding for the aviation research program (LuFo) has proven to be an effective means of providing targeted support for key technologies and of strengthening technological sovereignty.

This document was compiled by companies and institutions that are members of the Materials & Components Technical Committee of the German Aerospace Industries Association (BDLI). It emphasizes the strategic importance of materials development for the industry's future viability and demonstrates the opportunities that can be created through targeted, coordinated innovation policies.

**Dr. Matthias Miermeister**

Director Technical Development Engineering Global Aerospace, Novelis  
Chairman of the BDLI Materials & Components Technical Committee




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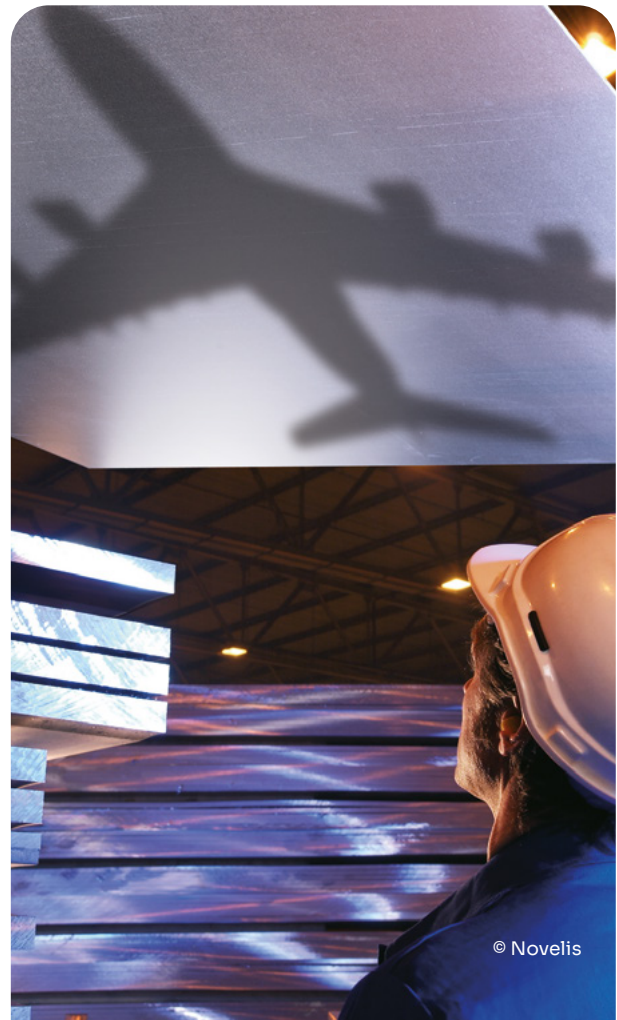
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## Executive summary and claims

The German aerospace industry is operating in an increasingly competitive global environment. The industry's goal is to leverage innovative materials and technologies to increase efficiency, safety, and sustainability, which are crucial for creating revolutionary next-generation aircraft and engine designs.

### Technological cornerstones

- The use of **lightweight construction materials**, such as aluminum and titanium alloys and **fiber-reinforced composites**, considerably reduces weight, improves corrosion resistance, and makes new production concepts and greater design freedom possible.
- Although **metallic high-temperature materials** (e. g., Ni alloys and materials produced by powder metallurgy) can increase efficiency in the engine sector, they still require optimization in terms of production costs and process quality.
- **Hybrid construction methods** involve optimizing specific component properties through the use of different material categories, associated with complex challenges, e. g., in testing and surface treatment.
- **Ceramic fiber composites** (CFC) are considered key to making significant fuel savings.
- **Highly efficient production technologies for future aviation applications**
- **Surface technologies:** Replacement of corrosion and erosion protection systems to meet REACH requirements, while maintaining functionality.
- **Additive manufacturing/3D printing:** Germany's global market leadership, centered on automation and quality assurance – both of which are crucial for adaptability and efficiency.
- **Eco-efficient technologies for a sustainable future:** Circularity for primary materials and energy-efficient processes.
- **Simulation to improve performance and shorten development cycles:** Although computer-aided materials and process simulations are essential, they are not yet an integrated standard practice across process chains.
- **Digitalization of industry and materials**



## Importance & outcomes

### Ensuring competitiveness

Long-term political framework conditions must promote innovative materials and manufacturing technologies.

### Sustainability & climate targets

Efficient, low-emission technologies and recycling strategies are key to decarbonizing aviation.

### Sovereignty & resilience

Mastering critical materials technologies allows for control over strategic supply chains and protects Germany from geopolitical dependence.

## Political demands

### R&D investments

Increase public and private funding for research and development – with materials-related topics receiving an appropriate share of the funding.

### Skilled labor offensive

Expand training and continuing education programs, as well as research, to ensure a supply of qualified professionals and maintain expertise in materials science.

### Defense and dual-use expertise

By leveraging its civilian expertise in materials science for military applications, Germany is strengthening its role as a reliable partner in the European security architecture.



## Conclusion

**Materials matter: The success of the next generation of aircraft and spacecraft depends on materials. For Germany to follow this path, the BDLI is calling for consistent political support in the areas of ecology, the economy, and security policy. To ensure long-term innovation, strength, and competitiveness, support for R&D, training initiatives, and industrial technology policy must work in tandem – in the interest of creating a self-reliant, sustainable, and future-proof industry.**

## Materials are our future

**The German aerospace industry is a high-tech sector. As such, it has the privilege of playing a leading role in shaping our future. This role comes with the responsibility of continuously overcoming new technological and economic challenges in a global market. The German aerospace industry maintains its leading international position by consistently conducting targeted research and development efforts to optimize existing products and ensure the successful market launch of future aircraft and spacecraft generations.**

The German aerospace industry relies on a highly developed value chain consisting of small and medium-sized suppliers, some of which are global market leaders in their respective fields (“hidden champions”); of large suppliers of complete structures and assemblies; of manufacturers of aircraft, helicopters, satellites, and autonomous flying systems – in Germany, for example, Airbus, Airbus Helicopters, and OHB; and of manufacturers of engines used in civil, military, and space applications – in Germany, for example, MTU Aero Engines, Rolls-Royce Germany, and Ariane Group.

Germany’s excellently positioned research landscape – which includes major institutions such as DLR and Fraunhofer Institutes as well as universities – and industrial enterprises together form a highly innovative network. This network provides unique opportunities for vertical integration, i.e., turnkey solutions for the industry’s needs.

When developing materials and processes for future generations of aircraft and spacecraft, special attention is going to enhancing energy efficiency and reducing weight. This involves the use of new, highly innovative lightweight construction concepts and materials. Especially in aircraft design, a low empty weight relative to the maximum takeoff weight is key to cost-effectiveness.

Commercial civil aviation is a dynamic and expanding global market. The German aviation industry plays a key role as a trusted partner within internationally interconnected supply chains, contributing – both directly and indirectly – to all major global programs.

Over the past two decades, global air traffic has shown steady average annual growth in the mid-single-digit percentage range. This development has gone hand in hand with sustained national support for pre-competitive research through the Federal Government’s aviation research programme (LuFo).

During this period, the German civil aviation industry has experienced substantial and continuous growth, reflected in a significant increase in both employment and overall industry turnover. More recently, the sector has continued to expand, with the civil aviation business of the German aerospace industry showing double-digit growth between 2024 and 2025 (source: BDLI).



↑ Channel fitting, Tital

The European and German aviation industries have played a significant role in shaping market trends and growth by making an early, forward-looking decision to focus on high-throughput and eco-efficient products, and they have performed exceptionally well in the global market. This leading position must be secured against competition from North America and China.

The growth of international air traffic shows no signs of slowing down. In the long term, global growth is expected to range from three to five percent per year. A decisive factor for the competitive positioning of the German aviation industry in the future is the speed at which robust, high-throughput innovations based on lightweight design principles can be developed and incorporated into the aviation products.

Aviation is synonymous with lightweight design because a low empty weight is fundamental for the flight performance, efficiency, and overall eco-balance of an aircraft.

In physical terms, flying is about overcoming two resisting forces with as little energy consumption as possible: air resistance and weight force. In an aircraft, the weight force results from three components: structural weight, payload, and weight of the fuel carried. In order to transport the payload (passengers, cargo, mission equipment, etc.) as energy-efficiently as possible, three adjustments are available: efficient aerodynamics, low-loss propulsion generation, and a low empty weight (aircraft structure, engine, landing gear, avionics, other components and equipment). The lower the empty weight, the more economically a passenger or cargo aircraft can be operated by minimizing fuel consumption or maximizing payload.

**Reducing the weight of an aircraft like an Airbus A320 by 100 kg translates to savings of approximately 10,000 liters of kerosene per year per aircraft for an airline (equivalent to approximately 25.5 tons of CO<sub>2</sub> per year per aircraft).**



The outstanding importance of lightweight design for the competitiveness of aviation products creates an extremely high pressure to innovate throughout the entire supply chain. It is estimated that in the aviation industry, €1,000–1,500 in extra costs are accepted for every kilogram of weight saved, while in the automotive industry this value is only €5–10/kg and in the railway industry only €1/kg.

Weight reduction through lightweight construction: The targeted use of advanced lightweight construction materials opens up substantial potential for weight reduction in engine construction. While these weight savings do not directly impact the engine's thermodynamic efficiency, they have a significant strategic impact on the aircraft's overall efficiency. Reduced engine weight results in lower structural and fuel requirements and supports key objectives such as reducing

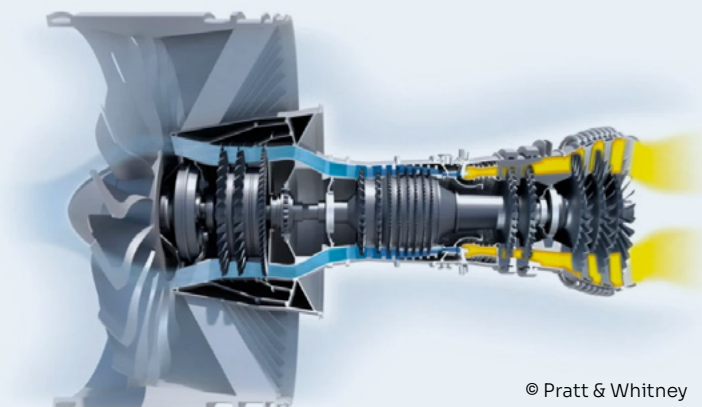
emissions, increasing range, and increasing payload, as outlined above.

Extending service life through improved high-temperature materials: Continuing the development of materials resistant to high temperatures is a key strategy for extending the service life of turbine components. For example, increasing the permissible operating temperature by about 15 °C through optimized Ni-based superalloys, ceramic matrix composites (CMCs), or innovative thermal barrier coating systems can double the service life of turbines without changing the engine architecture. An increase in temperature tolerance by 50°C can extend service life by up to eight times. These findings underscore the critical importance of materials development for the economic competitiveness and life cycle costs of future engine generations.

**Improving engine efficiency with high-temperature materials: For new engine designs, the increased temperature resistance of the materials used opens up two important strategic development options:**

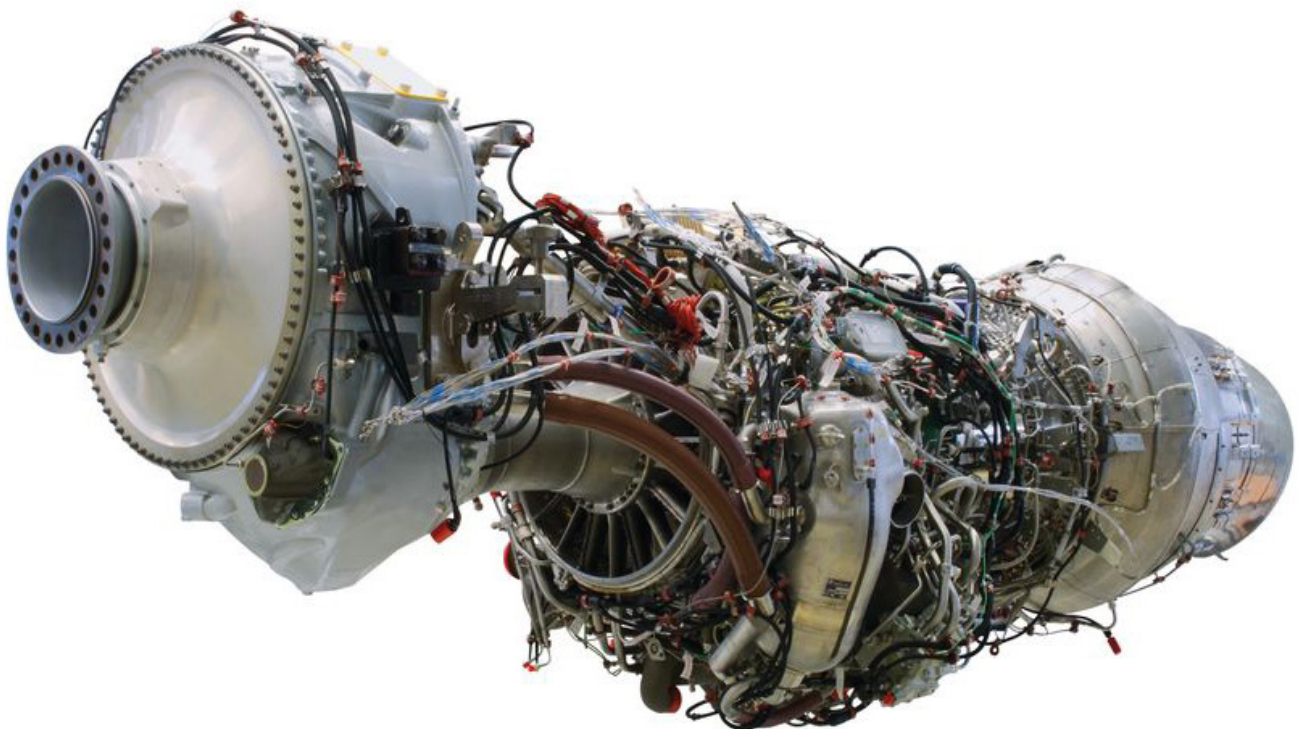
If the current cooling air requirements for hot components remain as they are, the ability for components to withstand higher temperatures makes it possible to reduce the size of the core engine. This allows for an increase in the bypass ratio and leads to a significant improvement in propulsion efficiency.

Alternatively, the cooling air requirement can be reduced and the core engine architecture can be unchanged. The air released in this way is then made available to the thermodynamic process, which improves the engine's overall efficiency, particularly by reducing specific fuel consumption (SFC).



Innovative design methods, materials, and processes help achieve the goal of continuously improving the economic efficiency and eco-balance of products in the German aerospace industry. These methods, materials, and processes are an integral part of national efforts to quickly capitalize on the opportunities arising from the digitization of industry. Contributions from the German aerospace industry are also used outside the sector, including in production automation, process simulation, materials characteristics, and process data acquisition.

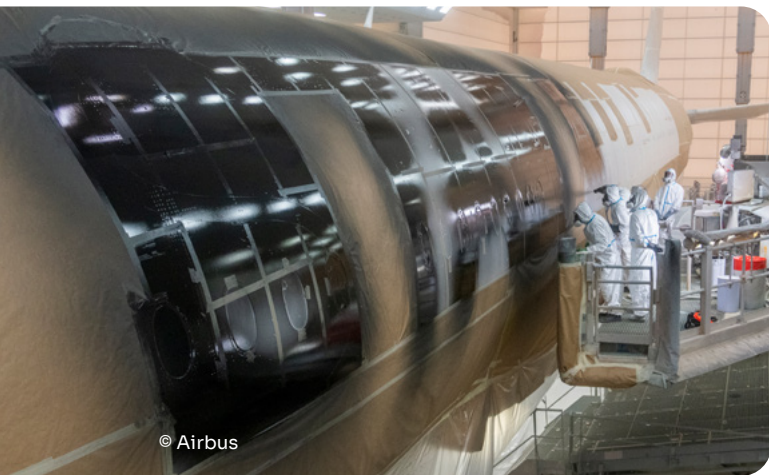
The industry has gained extensive experience with digital product life-cycle management systems (PLMS). However, the goals of the “factory of the future” go far beyond today’s solutions. These new prospects hold great potential for reducing costs, improving product quality, and increasing flexibility in production.



# Materials – the foundation of sustainable success

## Fiber-reinforced composites

**Carbon fiber-reinforced plastics (CFRP) are becoming an increasingly important strategic resource for the aerospace industry. Their greatest advantage is that they significantly reduce empty weight, which directly lowers fuel consumption and operating costs. In an industry where fuel consumption accounts for a large portion of life cycle costs, this property is of central importance, both economically and ecologically.**

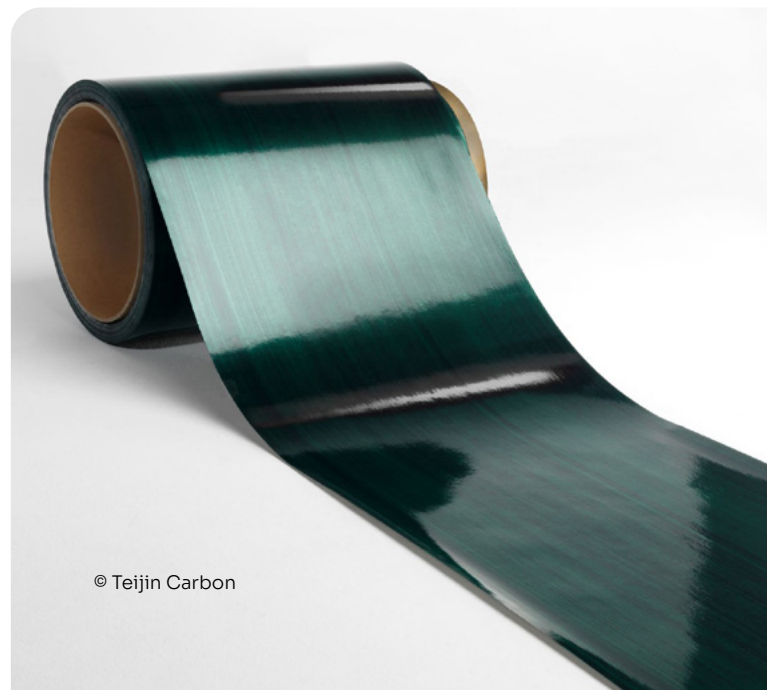


Currently, industry and research in Germany are focusing heavily on making CFRP economically scalable. The goal is to develop modular components that can be efficiently produced in large quantities using automated processes. This development makes CFRP interesting not only for long-haul aircraft but also for short- and medium-haul models, as well as for new mobility concepts such as urban air mobility.

Another focus is on closing the materials cycle. Advances in recycling are increasingly making it possible to reuse CFRP components at the end of their service life – a decisive step toward achieving climate targets by 2045. This significantly improves the carbon footprint over the entire life cycle when combined with reduced fuel consumption.

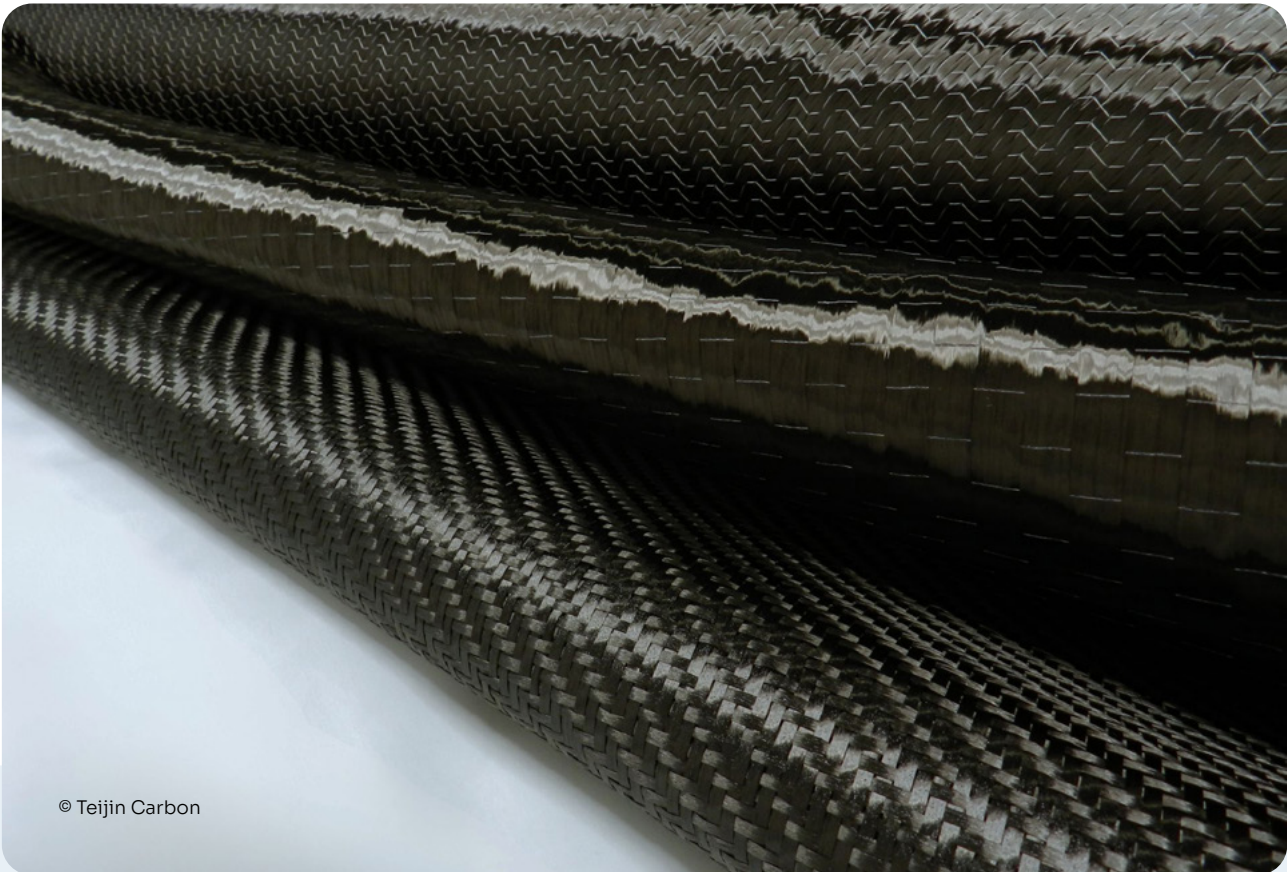
The development process focuses on optimizing the properties of carbon fiber and resin, particularly to achieve faster cycle times. These advances are crucial for industrial series production and the economic competitiveness of CFRP components.

CFRP is also indispensable for developing innovative lightweight structures where aerodynamic efficiency and structural performance are paramount. This is particularly evident in the blended wing-body (BWB) concept, which would be nearly impossible to implement without CFRP. The material properties make it possible not only to radically reduce weight but also to implement complex aerodynamic geometries.



Using digital twins also opens up new possibilities for monitoring materials: structural stresses and aging processes can be monitored in real time, reducing maintenance costs and increasing operational reliability.

This makes CFRP not only more efficient to use but also smarter, essential for moving us toward data-driven, sustainable aviation.



© Teijin Carbon

### European supply chain and CSR

Ensuring a European supply chain for fiber-reinforced composites is of strategic importance, especially for military applications. These materials are classified as critical and strategic raw materials (CSR) and are essential for manufacturing modern aerospace and defense systems. A European-controlled, independent supply chain provides

protection against geopolitical risks, ensures technological sovereignty, and guarantees the operational readiness of security-critical systems. Therefore, establishing and maintaining this supply chain is an indispensable prerequisite for the resilience and operational capability of European armed forces.

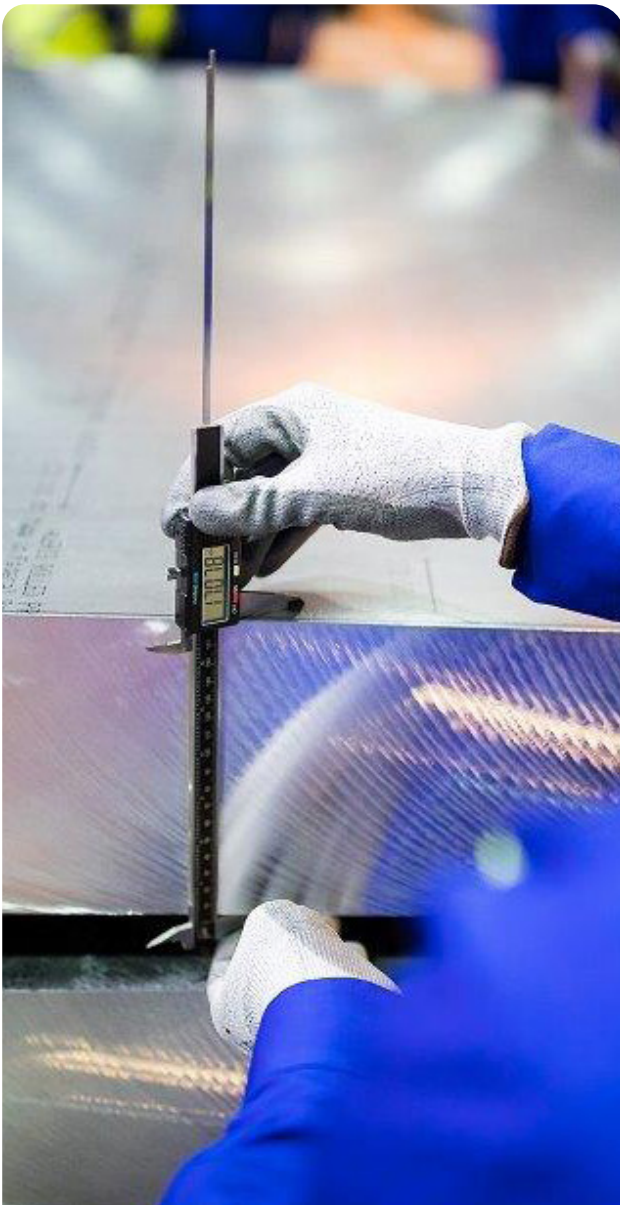
## Metals

**In the future, advances in high-strength aluminum alloys will make it easier to manufacture aircraft and helicopter structures using integral construction methods.**

In addition to developing alloys with better properties, using established materials more efficiently also offers considerable potential for lightweight construction and conserving resources. Thanks to new simulation methods that include new materials models and AI tools that can account for the anisotropy of material properties, complex structural components can be manufactured more cost-effectively from large forged or cast parts in the future. These parts have a significantly lower carbon footprint due to their low buy-to-fly ratio. Large drop-forged parts in the structural area (wings, fuselage, empennage) can

now be manufactured from high-strength, damage-tolerant aluminum alloys thanks to the availability of high-performance forging presses (press force >50,000 tons).

Advanced aluminum-lithium (AlLi) and aluminum-magnesium-scandium (AlMgSc) alloys as well as conventional 2XXX and 6XXX alloys that have suitable corrosion-resistant cladding are being further developed for use in fuselage planking and shell production. These allow for the use of highly productive joining technologies, such as friction stir welding (FSW), without sacrificing performance.



Leveraging proven manufacturing processes from the automotive industry, such as hot forming aerospace-grade aluminum sheets, can significantly increase productivity and efficiently scale up production rates.

Further functional integration and a reduction in the number of individual components are possible with the use of more thick and ultra-thick plates. When combined with appropriate manufacturing processes, such as explosive forming (also known as high-energy hydroforming), complex geometries and multifunctional structures can be efficiently produced.

Innovative recycling processes and coordinated scrap separation concepts ensure the efficient recycling of the large quantities of aluminum scrap generated during aircraft component manufacturing. Additionally, advanced end-of-life strategies allow for the return of disused aircraft parts to the materials cycle. This ensures the availability of raw materials and makes a significant contribution to a sustainable and resource-efficient aviation industry throughout the entire life cycle.

Titanium alloys offer significant potential for lightweight construction. Their high corrosion resistance and ability to be combined with fiber-reinforced composite structures make titanium alloys crucial to the aerospace industry. As in other applications, an integral design places higher demands on damage tolerance. For titanium alloys, this need can be met through proper thermomechanical treatment of the blank during production.

One new application of titanium alloys is in more efficient engines with larger diameters. This subjects the engine-mounting structural components to greater thermal stress, necessitating the use of heat-resistant titanium alloys.

→ Hydraulic forging press (pressing force 30,000 t) for the production of large titanium and aluminum structural components and for the production of forged drive discs made from titanium and superalloys, Otto Fuchs

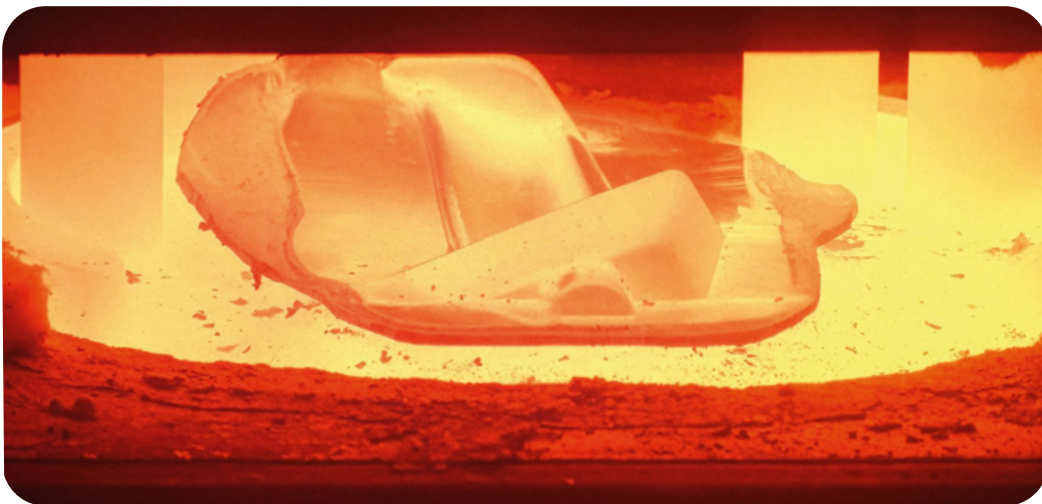
↓ Titanium forging for the Airbus A350, Otto Fuchs



## Metallic high-temperature materials

In the hot section of jet engines, new intermetallic alloys with a lower specific weight such as titanium aluminides (TiAl) have assumed a key function in recent years alongside nickel-based alloys. TiAl are processed using investment or near-netshape casting, with or without forging. Manufacturing technologies for TiAl turbine blades have been developed and are available in Germany, offering both cost-effectiveness and process reliability.

In addition to the alloys currently available, the materials class of intermetallics offers other materials systems with even better temperature resistance and considerable weight-reduction potential. An important aspect for future developments is a material-specific component design which takes best advantage of the materials' potential while taking into account the necessary damage tolerance.



← Isothermal forging of an engine blade made of titanium aluminide, Leistriz

Continued development of high-temperature, corrosion-resistant nickel alloy materials and semi-finished products helps increase the efficiency and durability of engine manufacturing. Novel nickel-cobalt alloys, so-called super alloys, already offer oxidation resistance, heat resistance up to an operating temperature of over 750 °C, and good hot formability and weldability.

The future requirements for new, innovative materials and alloys for higher application temperatures in the engine are currently being defined within the process chain for manufacturing semi-finished products from nickel and cobalt-based alloys.



↑ Turbine Blades, Access

## Hybrid construction methods

Combining metallic and fiber-reinforced materials opens up new opportunities for high-performance, resource-efficient aircraft structures. In addition to their traditional applications, innovative materials are becoming increasingly important for coating and insulation. Metallic protective coatings not only improve the erosion resistance of CFRP structures but also help to prevent galvanic corrosion.

Extending the use of hybrid construction methods hinges on developing suitable, environmentally friendly surface-treatment processes for corrosion protection.

Advanced thermal insulation systems based on ceramic barrier layers significantly improve thermal insulation and reduce weight in both the airframe area and engine components. Flame-retardant, multifunctional coatings – some of which have self-repairing properties – enhance the safety and service life of modern hybrid structures. These coatings are increasingly being digitally modeled to optimize manufacturing processes.



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## Next-generation materials – from concept to competitive product

**Only the availability of new, technologically advanced materials makes it possible to implement the revolutionary design concepts currently under development for the next generation of aircraft and spacecraft. To achieve this, new methods must be developed for testing materials, optimizing designs, and determining material properties. Only then will there be a chance of creating competitive products.**

For future applications, a number of highly innovative materials such as aerogels and smart materials are currently in basic research projects being evaluated for suitability for multifunctional lightweight structures. For Germany, industrializing these materials would represent a significant technological milestone and a way to safeguard the future.

In the hot section of engines, fiber-reinforced ceramics (ceramic matrix composites) show great potential for reducing fuel consumption due to their unique combination of low weight (about 50% of comparable nickel-based alloys) and maximum temperature resistance. The key to a broader introduction of fiber-reinforced ceramics is a design suitable for the material and the availability of a competitive process chain from the fiber to the finished product, including the necessary surface coating technology.

Two material groups of fiber-reinforced ceramics are currently being developed for technical applications: oxide fiber-reinforced ceramic composites with oxide ceramic matrix (Ox/Ox), and silicon carbide fiber-reinforced ceramic composites with a silicon carbide matrix (SiC/SiC).

Using fiber-reinforced ceramics in the engine is a groundbreaking decision. Competitors from around the world are already using the first components made from this material. Several technology projects aimed at qualifying fiber-reinforced ceramics for industrial use in Europe and Germany are already underway.

Improved numerical design methods will be crucial for better exploiting the structural mechanical performance potential of fiber-reinforced composites.

## Highly efficient production technologies for future aviation applications

**Implementing innovative, high-throughput, lightweight construction concepts requires improvements to existing manufacturing processes. Supporting design and testing methods are equally important, including numerical design methods for a design suitable for materials and production, cost-effective non-destructive testing methods, and modern, cost- and time-efficient repair methods.**

When processing fiber composites, the focus is on automated production methods with higher lay-up rates. Large structures, such as fuselage planking for the Airbus A350XWB, are already produced using fully automated laying processes. Further development and optimization are required for material throughput per time unit, particularly for complex, double-curved geometries.

To produce future product categories with potentially high quantities, such as advanced air mobility and drones for defense, the efficiency and flexibility of manufacturing technologies will be crucial.

Although a higher degree of automation increases the efficiency of processing thermosetting prepreg materials, consolidating them usually requires the energy-intensive autoclave process. However, new out-of-autoclave technologies, such as digitally controlled vacuum infusion with integrated sensors, allow for precise and reproducible curing in an oven under standard vacuum conditions. These processes allow for the cost-effective manufacturing of large-area, thick-walled integral structures, such as wing boxes and high-lift components, while maintaining high production rates and reducing environmental impact.

Not every structure benefits from a fully integral design. Stiffening elements, such as stringers, can be efficiently and affordably produced in large quantities using automated processes and then combined with structural elements to form stiffened shells. Structural

bonding of CFRP is becoming increasingly important, especially for ZEROe, due to new automated pretreatment processes that digitally control cleaning, activation, and adhesive application. Advances in inline quality assurance, such as sensor-based surface analysis and non-destructive defect detection, already make it possible to reliably evaluate bonded joints during production. These advances are crucial for ensuring process reliability and reproducibility.



Thermoplastic semi-finished products are becoming increasingly strategically important as materials for CFRP components – especially for automated, resource-efficient production. Thanks to their weldability, semi-crystalline thermoplastics make new joining processes such as laser and ultrasonic welding possible, allowing for designs that do not require many rivets. These technologies are being industrialized through close collaboration between research institutions, OEMs, and specialized SMEs. Projects such as the Multifunctional Fuselage Demonstrator show



→ Integrated engine disk (blisk) for the Airbus A400M: The image shows the forged blank (left, Otto Fuchs) and the finished component (right, MTU Aero Engines). The integral “bladed disk” design achieves high structural efficiency. A blade-close contouring already during the forging process also enables a substantial reduction in machining effort and increases material utilization. (BliDes\_HDV, LuFo IV)

that thermoplastic CFRP structures are not only ecologically advantageous but also economically scalable, offering production times up to 40% shorter and significantly reducing material waste.

However, joining thermoset and thermoplastics at the seams of components manufactured using hybrid technology remains a challenge.

German suppliers are technological leaders in the manufacture of semi-finished products and in processing titanium and high-temperature materials. The major challenge is maintaining and expanding this technological leadership in competition with low-wage regions. The key to success lies in resource-efficient production of raw parts using near-net-shape technology, the continued development of machining processes, the optimization of tool concepts in conjunction with a high degree of automation, and the development of efficient quality monitoring and assurance methods.

There is significant innovation potential in the field of manufacturing technology for metallic materials. Modern welding processes such as friction stir welding, laser welding, and linear friction welding, as well as advanced forming processes such as creep forming for AlMgSc materials, combined with modern, proven aluminum alloys, allow significant increases in production rates.

These increases are necessary to meet industrial challenges related to the ever-increasing demand for large metallic structures (e.g., fuselage shells for the next generation of single-aisle aircraft).

In the field of engine manufacturing, a key focus is on high-precision and cost-effective manufacturing technologies for processing high-strength titanium- and nickel-based alloys. The components relevant for engine construction are subject to the highest aerodynamic, thermal, and structural-mechanical requirements during operation. The German industry’s competitive position is ensured by its expertise in the production of these components.

The novel high-strength materials systems currently under development are more difficult to form, so improved forming processes must be devised in order to exploit these new alloys’ potential. Alongside continuing to optimize the conventional machining processes such as milling, turning, and grinding, new and ongoing development of alternative processes are also on the agenda. These include electrochemical processes that remove metallic materials with high precision without applying heat or force. In addition to laser-assisted manufacturing processes, the existing chemical vapor deposition (CVD) and physical vapor deposition (PVD) processes must be further developed to apply novel coating systems that protect against oxidation, corrosion, and erosion.

A completely new value chain must be established for high-temperature-resistant fiber-reinforced ceramics, ranging from fiber suppliers through semi-finished product suppliers to OEM manufacturers. The use of ceramic materials such as  $\text{Al}_2\text{O}_3$  or SiC as abrasives underscores the significant challenge of developing cost-effective machining processes, including the testing technologies necessary for these materials.

Hybrid designs made of aluminum, titanium, or superalloys, with or without fiber composite content, are considered to have significant technological and economic potential. However, in hybrid construction methods, structural bonding and joining face particular challenges regarding surface activation and the integrity of joined surfaces under operating conditions in flight. Automated laydown techniques for producing thin-walled hybrid structures are currently being developed for use in aerospace and defense technology applications, such as the construction of unmanned aerial vehicles.

In Germany, a high-wage country with high energy costs, the focus is shifting toward systematically increasing production efficiency. A key element is the implementation of automated processes with integrated monitoring and inspection systems, which together form the “factory of the future.” The comprehensive digital networking of production resources within the supply chain builds on this concept. These systems enable precise planning and prediction of robust production processes, extending all the way to real-time control and regulation.

Production processes must fulfill the criteria of sustainable production throughout the entire process chain in order to meet the ambitious goals of the European aviation industry within the framework of the ACARE agreements (Advisory Council for Aviation Research and Innovation in Europe) regarding emission and noise reduction. Support at the European and national levels through appropriately equipped and structured research funding programs has proven to be effective and extremely successful in this context.

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## Surface technology as a decisive interdisciplinary technology

Along with the continuous ongoing development of materials and manufacturing processes, research in the field of surface technology is of outstanding importance. Strict environmental, occupational health, and safety requirements, as well as strict requirements from the European chemicals regulation REACH (Registration, Evaluation, Authoriza-

tion, and Restriction of Chemicals), necessitate replacing existing surface-protection systems such as coatings and lacquers that contain hazardous ingredients. The primary objective must be to continue to fully ensure the necessary functionalities, such as varnish adhesion, corrosion and erosion protection, and surface quality.



Other key areas of activity in surface technology include the identification and future avoidance of critical elements or compounds due to environmental and health risks (e.g., PFAS – per- and polyfluoroalkyl substances, often referred to as forever chemicals), as well as the development of alternatives for rare earth elements or elements with politically fragile supply chains.

Comprehensively addressing all the critical aspects of surface technology requires decisive, early action with a long-term perspective.

The German industry is considered a global leader in this field, with internationally recognized experts in research institutions, materials development and manufacturing, automation technology, and quality control. Nevertheless, considerable additional efforts are needed to overcome the technical challenges posed by the increasing use of fiber-reinforced composites and hybrid CFRP/metal construction methods.

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## Additive manufacturing – ensuring and expanding a national core competence

In recent years, additive manufacturing processes have developed from a promising innovation into an established technology. In the aerospace industry, this technology is now an integral part of the mass production of structure, system, cabin, and engine

components. The broad technology portfolio includes processes for manufacturing components from metallic and polymer powders, as well as wires or filaments. These materials are fused layer by layer using laser- or electron-beam processes or hot nozzles.

Additive manufacturing enables the production of complex geometries and allows entirely new designs, such as those based on bionics. This process creates highly durable, lightweight, and functionally integrated components inspired by natural structures; these components can only be produced using additive manufacturing and increase efficiency in aviation.

Quality assurance is one of the central challenges of additive manufacturing and is a multidimensional field. Real-time process monitoring, innovative nondestructive testing methods, and simulation-based analyses throughout the entire process chain are crucial for improving process stability and component quality. Germany holds a leading position in this technology sector and should systematically expand its additive manufacturing capabilities. The goal is to reliably and economically implement complex applications in series production.



↑ Bionically optimized bracket, MTU Aero Engines

Developing suitable materials for 3D printing is a top priority when it comes to the raw materials required for this process. These include high-quality plastics, metallic powders, and aluminum, titanium, and nickel alloy wires for the powder bed process and processes with a higher productivity rate (high deposition rate additive manufacturing). The mechanical properties of polymer-based 3D-printed components can be improved by integrating short, long, or continuous fibers.

The economic efficiency of additive processes largely depends on process stability and the cost-efficiency of the associated upstream and downstream machining processes. Additionally, significant efforts are being made to develop processes, procedures, and technologies to monitor and ensure the quality of additively manufactured components. Powerful, physics-based simulation processes for materials and for the printing process are deepening understanding of the process. For the technology to be adopted more broadly, calculation methods that have been validated through experiment must be available. These must be able to predict the service life and damage tolerance of components, considering process-related residual stresses, as well as internal and external process-related defects. For 3D-printed engine components, the influence of mechanical, thermal, and chemical operational loads must also be considered. This is particularly important for repair procedures based on 3D printing processes, for which operational safety and achievable service-life extension must be estimated numerically and validated through experiment.

## Eco-efficient technologies for a sustainable future

Increasing the efficiency of both materials and manufacturing technologies significantly contributes to environmental protection. Energy requirements, water consumption, and emissions are drastically reduced throughout the entire process chain. State-of-the-art manufacturing processes ensure the best possible use of high-quality materials deployed in aerospace technology.

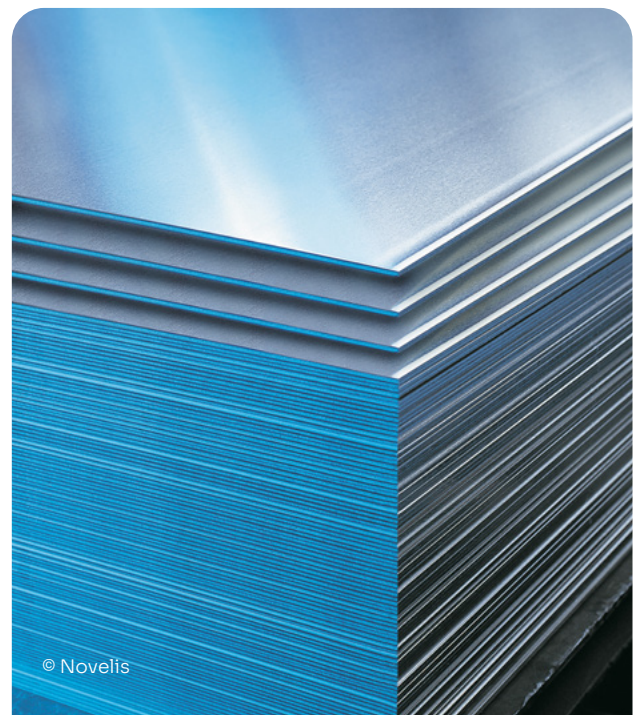
Consistent continuing development of fiber composite and metallic materials, as well as the technologies at the interface of these material groups, makes hybrid structures (e.g., metal/CFRP) and hybrid designs possible. This also leads to the development of new material concepts for applications in new innovative electric drives and energy storage systems, such as those being developed for unmanned aerial vehicles (UAVs) and urban air mobility (UAM).

Current lacquer systems and surface technologies are being improved upon to align with REACH requirements. Particular attention is being paid to developing surface systems with self-cleaning properties, improved corrosion protection, an active contribution to minimizing surface resistance, and an extended functional spectrum (functional coatings).

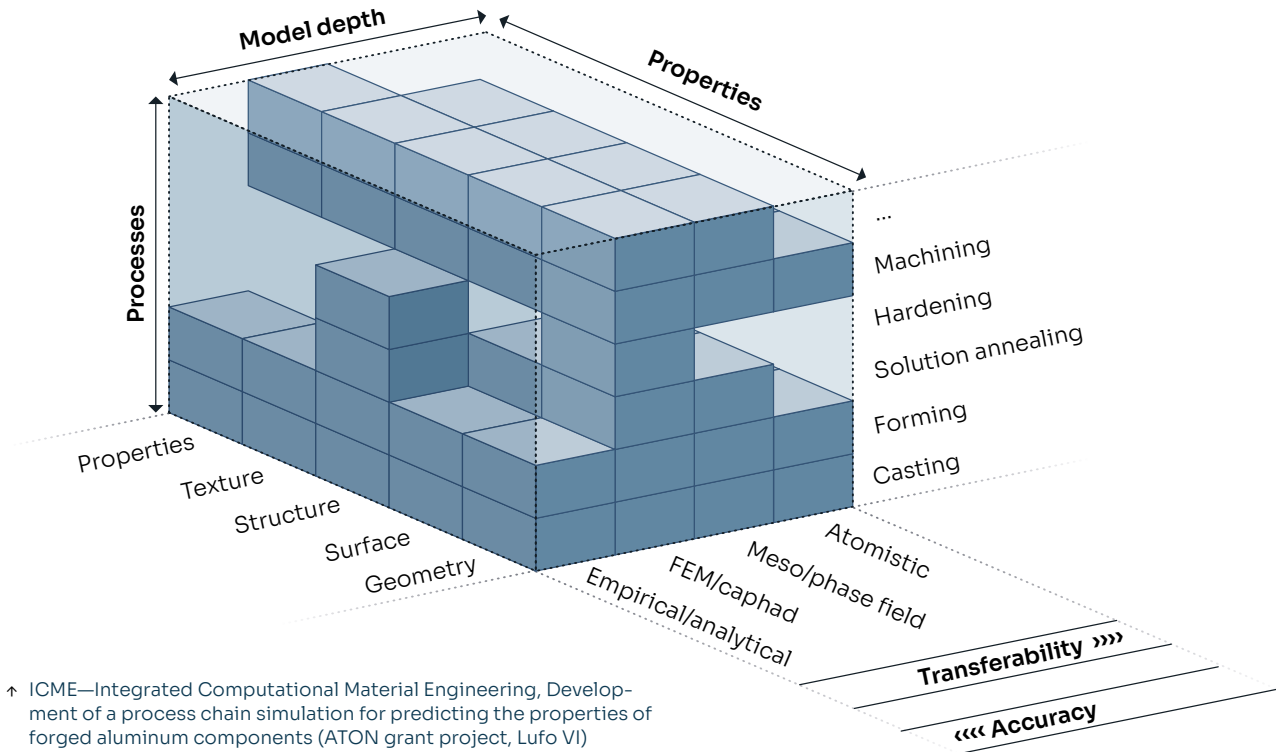
Another area of focus is the establishment of closed materials cycles. Although there are already established recycling processes for aluminum and nickel alloys, titanium alloys, a strategically important group of materials, are becoming increasingly significant. In Germany, efforts are underway to establish a national titanium recycling facility.

This initiative is driven by uncertainties in international markets, including potential future trade restrictions and tariffs, as well as dependence on a few geopolitically critical supply sources. The goal is to strengthen the resilience of Germany's domestic aerospace and defense industries and ensure a reliable titanium supply. Reuse is also a key focus when it comes to CFRP materials. For a long time, technical difficulties in separating polymers and carbon fibers meant that fiber composite blend was simply incinerated or used as a filler material in injection molding.

Modern CFRP recycling processes follow two main approaches: First, production scraps are mechanically processed with minimal effort and reused in less demanding applications, such as injection-molded parts. Second, advanced processes, such as pyrolysis and laser processing, make it possible to recover almost 100% of high-quality carbon fibers. These fibers can be processed into new semi-finished products and re-impregnated with polymer materials. Currently, recycled fibers are 88% as strong as virgin fibers and make an important contribution to sustainability and resource conservation.



## Simulation to improve performance and shorten development cycles



Simulation is the way to shorten the innovation cycles the necessary amount. It enables upstream virtual development and testing of new aircraft designs while simultaneously providing verifications important for certification.

In the field of materials and manufacturing process development, computer-aided simulation has become essential for success. The strategic significance of a simulation that spans process chains, consistent with an integrated computational materials engineering (ICME) approach, was recognized early on. A number of research and development projects are now in progress in this area. Nevertheless, the ICME tools currently available for materials and process development are generally useful only for analyzing specific

issues, or are used only for known materials. A comprehensive overview of the process chain has yet to be achieved, which often prevents the development of new, improved materials. Rapid prototyping based on such an overview would significantly accelerate product development. The value of ICME for materials and process development will only reach the necessary level when the predictive accuracy of simulation tools improves through the use of AI tools or surrogate models that enable faster calculations. The latest developments in quantum computing, in particular, can raise the performance of ICME models to a new caliber. This makes ab initio calculations in the atomistic range possible, allowing prediction of the properties of novel alloy systems.

It is essential to first simulate the aircraft concept on a computer, taking into account all development and manufacturing requirements, and to “fly” it under realistic, software-generated conditions. This system makes it possible to reliably optimize components long before they are physically available, saving time. As a representation of the real product, the virtual aircraft or “digital twin” must provide all necessary development data regarding its characteristics and capabilities.

Many of the prerequisites for the virtual aircraft have already been developed as part of the German aviation research program (LuFo). Germany is poised to play a leading role in this area due to its broad-based experience and expertise in the field of simulation.

The virtual model also connects the product to the supply chain. It facilitates early coordination within the supply chain, data exchange, and cross-functional collaboration during the

detailed design phase of the development process. In this context, IT standardization, networking, and access to high-performance computers are essential. Industry-specific cloud applications will then open up new possibilities for transnational interaction and communication in industrial logistics and automation-oriented design.

Shortening product development times is essential to maintain competitiveness in the global market. A stronger market position can be achieved by integrating a wider range of engineering disciplines more closely in the early stages of product development. The determining factor here is the integration of the relevant numerical simulation capabilities and virtual design tools. In addition to the physical behavior of the structures, the simulation also records the optimization of manufacturing processes and production costs.

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## Digitization of the industry and of materials

**The digitization of the aviation industry, particularly in the field of materials, is highly complex:**

- Safety considerations are paramount throughout an aircraft’s entire life cycle. The demands placed on the supply chain to meet strict safety requirements are high.
- An aircraft is a highly complex technical product. Large aircraft consist of over one million individual parts.
- The market demands a high degree of flexibility in adapting and configuring the base aircraft and interior to meet customer requirements.
- The value chain is international and includes a large number of suppliers. Development, production, service, logistics, and maintenance are typically distributed across multiple locations.

To test the interplay of new technologies and assess the risks of making changes to production methods, it is necessary to demonstrate their feasibility in a model environment. This allows the introduction of new technologies and material concepts – even as production volumes ramp up, one of the key ongoing challenges in the aerospace industry – with manageable risk.

Short-term goals include networking production equipment and automatically recording and recognizing components, including their positions, shapes, and any deviations from defined quality characteristics. The medium-to long-term goal is to implement automated, fault-tolerant processes that automatically make corrections when deviations occur and to further improve cooperation between humans and machines equipped with intelligent sensors in the production environment.

A digital factory offers the capabilities to accurately plan and predict production processes, all the way through to real-time monitoring and control of production operations. The aim is end-to-end data acquisition in the production flow, including production modeling and process simulation, as well as advanced visualization and the use of augmented reality, which artificially expands knowledge and sensory perception.

Unlike many other sectors, German companies in the aerospace industry generate most of their added value domestically. This is made possible in particular by increasing the degree of automation in production and continuously optimizing process design and quality control.

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## Digital material and product passports – transparency across the entire life cycle

Complete digital documentation of materials and products is becoming a key tool for the aerospace industry. Digital material passports (DMPs) and digital product passports (DPPs) provide the transparency required throughout the entire life cycle, from extraction of the raw materials to processing and recycling.

### Regulatory drivers and compliance

The European Union is promoting the adoption of digital product passports through various regulations. The EU Battery Regulation (2023) already mandates digital passports for batteries. The Ecodesign for Sustainable Products Regulation (ESPR) will gradually extend this requirement to additional product groups. This results in specific requirements for the aviation industry:

- **Carbon Border Adjustment Mechanism (CBAM):** Starting in 2026, CO<sub>2</sub> emissions from imported materials, such as aluminum, steel, and other metals, must be reported. Digital material passports will enable seamless documentation of the product's carbon footprint across the entire supply chain.
- **Corporate Sustainability Reporting Directive (CSRD):** Companies are increasingly required to disclose detailed sustainability information about their supply chains. DMPs provide the necessary data at the component and materials levels.
- **Critical Raw Materials Act (CRMA):** It is becoming mandatory to document critical raw materials, such as scandium in AlMgSc alloys, rhenium in Ni superalloys, and carbon fibers, to ensure resilience and security of supply.

### Technical and economic advantages:

Digital Material Passports offer far more than just regulatory compliance. They create real added value throughout the entire value chain.

- **Quality assurance and traceability:** Complete documentation of materials' properties, including batch numbers, heat treatment protocols, and mechanical test results. In the event of quality deviations or incidents, the affected batch can now be identified in minutes rather than weeks.
- **Optimized maintenance and extended service life:** Knowing the material's history and load profiles allows for optimized maintenance intervals and extends the service life of the component. This reduces costs and increases availability.
- **Circular economy and recycling:** Knowing the precise composition of an alloy and how it was pre-treated is essential for efficiently recycling high-quality aerospace alloys. DMPs allow for the recycling of materials grouped by type with minimal quality reduction and maximum value retention.
- **Supply chain resilience:** During times of geopolitical uncertainty, data management platforms offer greater transparency about the origin of critical materials and help reduce dependencies by identifying risks early on.
- **Dual-use and defense applications:** In military applications, complete documentation of material origin and processing is essential for safety reasons. DMPs fulfill these requirements digitally and in accordance with audit requirements.

### Challenges and solutions:

The introduction of digital material passports in the complex aviation supply chain faces several challenges:

- **Data sovereignty and data security:** Sensitive material and process data must be protected while specific information is shared throughout the supply chain. Solutions are offered by modern data trustee concepts and decentralized data architectures.
- **Standardization and interoperability:** Different systems must be able to communicate with each other. Standardized data models and interfaces are required here.
- **Legacy systems:** The service life of many aircraft is 20–30 years. It must be practical to integrate DMPs for existing fleets.
- **International cooperation:** The global aviation supply chain requires the international coordination of data formats, access rights, and security standards.

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## About the aerospace industry

The German aerospace industry, represented by the BDLI e.V., is an integral part of the European aerospace industry. As a key strategic industry, the sector plays a decisive role in the technological and economic sovereignty of the European Union. It promotes economic growth, technological innovation and international connectivity. In Germany alone, the industry contributes significantly to GDP with over 130,000 employees and an annual turnover of over 62 billion euros.

Over the decades, Europe has worked together with industry, member states and the European Union to achieve a leading position in the aerospace industry. This must be maintained and further expanded in the face of international competition. In view of far-reaching technological, political and industrial changes, this requires sustained investment in research and innovation.

### German Aerospace Industries Association

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