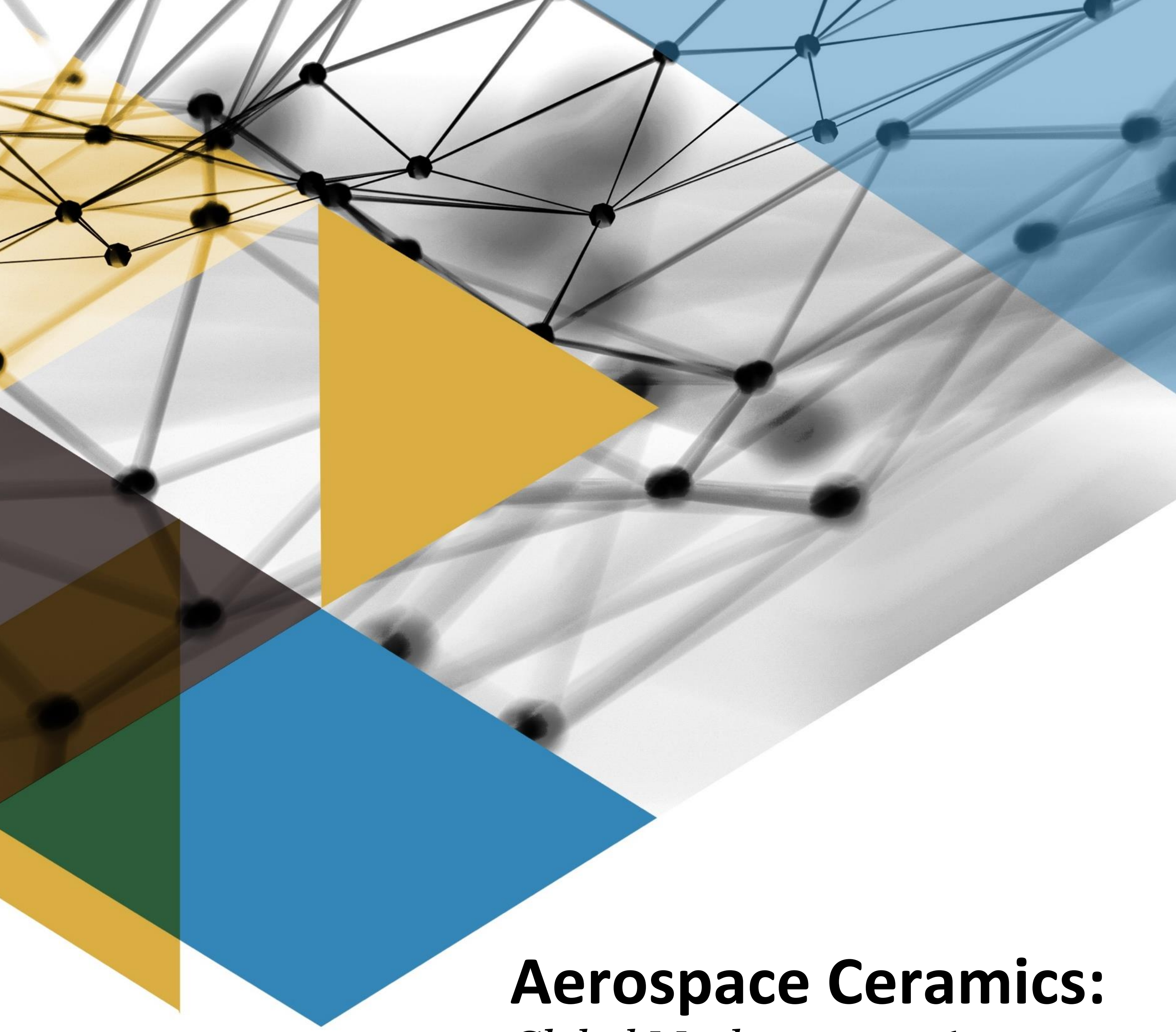

Aerospace Ceramics:

Global Markets to 2026

October 2021

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bcc Publishing

Report Code: AVM218A

Additional segmentations and data sets available upon request. Email custom@bccresearch.com

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Chapter 1

Introduction

Chapter 1: Introduction

The term ceramics primarily refers to material made of clay and which has limited applications such as for pottery and insulating material. However, today ceramics are developed through various production processes and different materials such as metals and non-metals to make them suitable for a wide range of industrial applications. These applications include automotive, electrical and electronics, biotechnology, and industrial manufacturing.

Ceramics are used in the aerospace industry due to their high thermal resistance, chemical stability, high hardness, and high vibration resistance. These materials are lighter than metals and provide better electrical insulation and energy ablation.

Aerospace applications can be segmented into three major categories: thermal, electrical and structural applications. The materials used are classified as oxides, non-oxides, glass ceramics, and ceramic matrix composites (CMCs). These ceramics are used in components of an aircraft that must have high compressive strength, such as engines and exhaust systems.

The COVid-19 pandemic had a negative impact on the commercial aerospace segment due to travel shutdowns, low passenger counts and high declining ratio in 2020. However, the defense aerospace segment was comparatively not heavily impacted as the untouched since purchase commitments were made well before the pandemic.

Study Goals and Objectives

The goal of this study is to provide an up-to-date analysis of current and future markets for aerospace ceramics. The study provides a comprehensive accounting of worldwide aerospace ceramics markets. It presents a thorough and up-to-date global assessment of the market and business of aerospace ceramics. This, in turn, will help industry participants, suppliers and manufacturers make informed decisions needed to compete and succeed in the marketplace.

Reasons for Doing This Study

Aircraft manufacturers are increasingly incorporating ceramics and composites into aircraft to reduce weight and increase fuel efficiency. Ceramics also help manufacturers cope with tightening emission norms across the globe. Companies are actively investing large amounts in research to develop better-performing ceramics and composites. This has put ceramics in the spotlight as a lucrative opportunity for stakeholders of the aerospace materials industry.

This study will help aerospace ceramics manufacturers, raw material suppliers, aircraft and component manufacturers, along with other stakeholders to stay abreast of the technology and the demand for it in the years ahead.

Scope of Report

This report provides definitive estimates and forecasts of the global market, as well as a detailed analysis of the markets in specific regions and countries, ceramic material, industry segments, and applications and ongoing trends.

In this report the aerospace ceramics market is segmented by material, segment and application. Recently, thermal and structural applications have been at the center of research and development activities for aerospace ceramics. Carbon-based composites are gaining popularity in structural applications in the aerospace industry.

Information Sources

BCC Research conducted comprehensive secondary research that included technical papers, news articles, magazines, journals, White papers, and company websites. Trends were identified and verified through primary and secondary sources.

Methodology

The market estimation is a result of combined study through primary and secondary research. BCC Research conducted a detailed literature search referring to news, articles, journals, technical reports, and related websites. Various press releases of regulatory bodies and presentations from industry players were also accessed during the study. This secondary research helped in identifying current market trends, segmentations, key players, and market dynamics along with major factors influencing the value chain. The aerospace ceramics segmentations were estimated based on the product mapping of leading industry players and technical papers available online.

The aerospace ceramics value chain is comprised of multiple stakeholders such as raw material suppliers, ceramic component manufacturers, subcomponent manufacturers/assembles, and original equipment manufacturers. Primary research included connecting with industry experts from all the relevant nodes of the value chain. Interviews were conducted with help of Skype, mail and telephone. The findings from secondary research were validated through the primary research. The market estimations and forecast were adjusted based on the qualitative and quantitative information obtained from these interviews.

Geographic Breakdown

In this report, the geographic regions considered for market analysis include, and only include:

North America

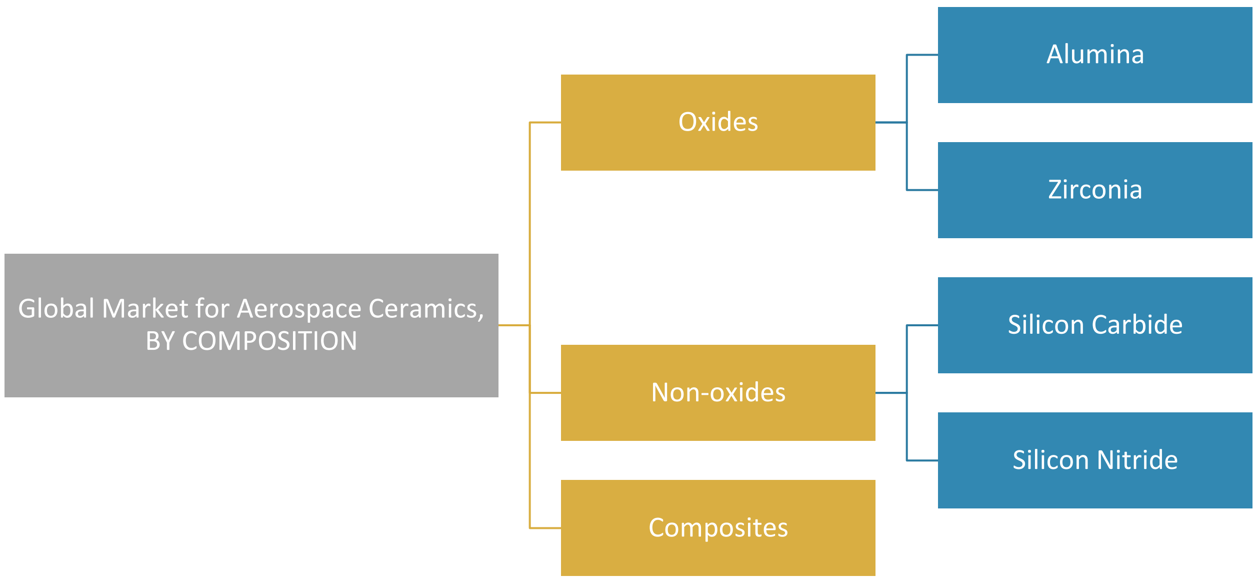
- United States.
- Canada.

- Europe
  - France.
  - U.K.
  - Germany.
  - Rest of Europe (Italy, Spain, Russia).

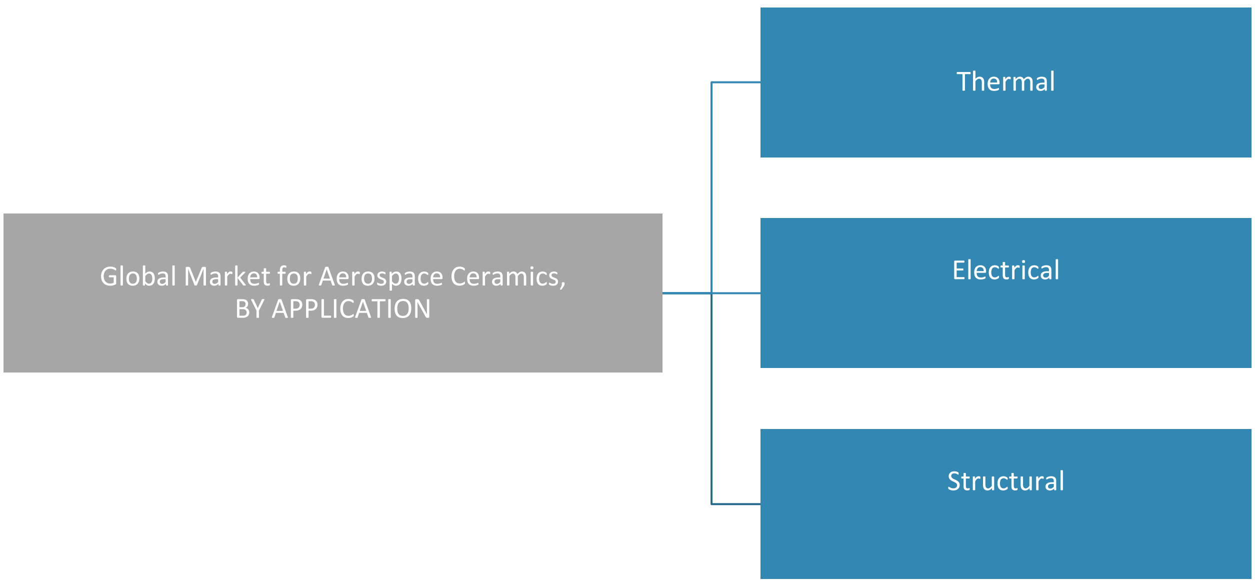
- Asia-Pacific
  - Japan.
  - China.
  - South Korea.
  - Rest of APAC (India, Singapore, and Australia).

Rest of the World (RoW).

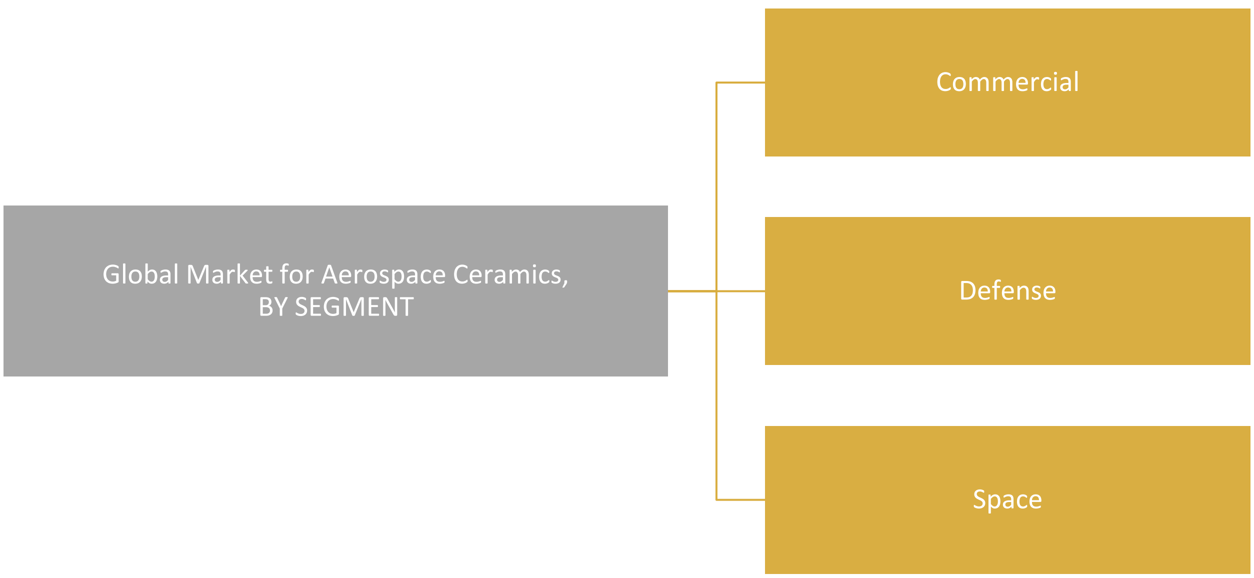
Global Market for Aerospace Ceramics, by Composition



Global Market for Aerospace Ceramics, by Application



Global Market for Aerospace Ceramics, by Segment



Analyst's Credentials

BCC Publishing Staff comprises expert analysts who are skilled in conducting primary research, secondary research and data analysis and have decades of combined experience covering a wide range of industries, including healthcare, advanced materials, and emerging technologies. Collectively, the team represents a diverse set of educational achievements with individual graduate work completed in fields such as microbiology, electrical engineering, business administration, and surgery, among others.

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Related BCC Research Reports

- AVM192A *Global Markets for Emerging Materials in Aerospace.*
- CHM137A *Thermal Ceramics: Technologies and Global Markets.*
- AVM198A *Advanced Materials for Extreme Environments: Global Markets.*

Chapter 2

Summary and Highlights

Chapter 2: Summary and Highlights

The global market for aerospace ceramics was valued at $4.7 billion in 2020, although it was slowed during the year by the COVID-19 pandemic. It is estimated the market will grow at a compound annual growth rate (CAGR) of 12.2% from 2021 to 2026 to reach $8.8 billion in 2026. Composites such as carbon-fiber reinforced polymer (CFRP) and glass-fiber reinforced polymer (GFRP) are experiencing high demand for structural applications in aerospace materials. Thus, the ceramic composites segment will dominate the market by composition during the forecast period.

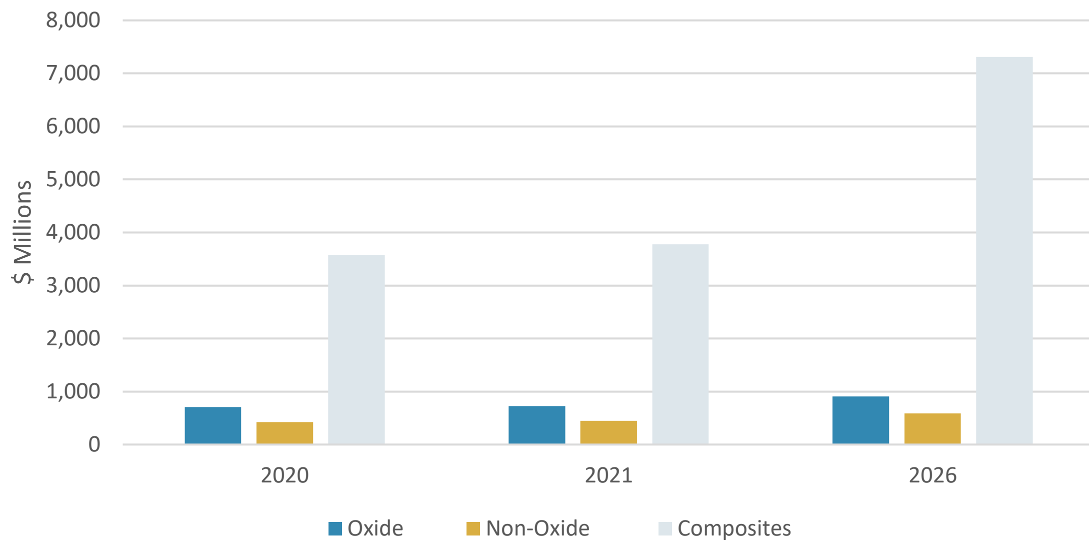
Summary Table: A
Global Market for Aerospace Ceramics, by Composition, Through 2026
($ Millions)

Composition	2020	2021	2026	CAGR% 2021–2026
Oxide	706.3	727.5	906.6	4.5
Non-oxide	423.8	449.2	589.9	5.6
Composites	3,578.6	3,774.0	7,312.1	14.1
Total*	4,708.7	4,950.7	8,808.5	12.2

*Note: Totals in this report's tables may not match exactly because of rounding issues.

Source: BCC Research

Summary Figure: A
Global Market for Aerospace Ceramics, by Composition, 2020–2026
($ Millions)



Source: BCC Research

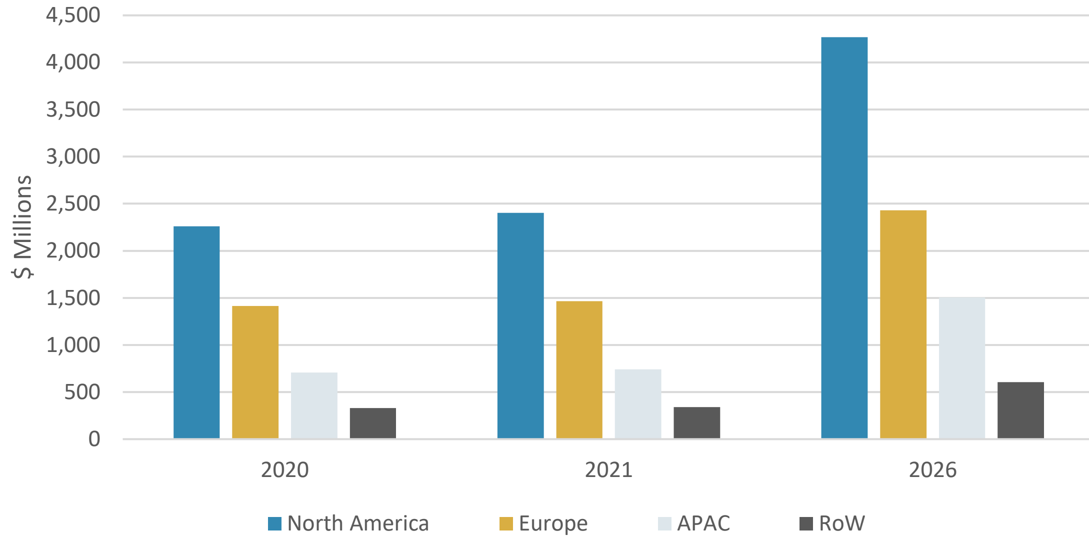
North America and Europe lead in the consumption of aerospace ceramics due to a high concentration of commercial and defense aircraft manufacturers in the regions. The aerospace ceramics market in these regions is primarily driven by the demand form Boeing and Airbus production facilities, respectively. With steadily growing demand for military aircraft and the emerging private space industry, North America is expected to remain the largest market for aerospace ceramics during the forecast period.

Summary Table: B
Global Market for Aerospace Ceramics, by Region, Through 2026
($ Millions)

Region	2020	2021	2026	CAGR% 2021–2026
North America	2,260.2	2,404.3	4,267.6	12.2
Europe	1,412.6	1,466.4	2,430.0	10.6
APAC	706.3	740.5	1,506.6	15.3
RoW	329.6	339.5	604.3	12.2
Total	4,708.7	4,950.7	8,808.5	12.2

Source: BCC Research

Summary Figure: B
Global Market for Aerospace Ceramics, by Region, 2020–2026
($ Millions)



Source: BCC Research

The key driver of growth in the aerospace ceramics market is the growing space industry. The demand for small satellites (micro, nano satellites) for telecommunication, surveillance and entertainment purposes is increasing at an exponential rate. Also, the recovery of the commercial aircraft industry and stringent emission norms will play significant roles in the future demand for ceramics.

At the same time. the aerospace ceramics market faces challenges such as large volume and thick component production; along with brittleness, repair techniques and reproducibility. Also, the materials' high resistance to heat, electricity and chemical reactions causes difficulty in the waste disposal of ceramics and composites.

Some of the major players in the market are 3M (U.S.), CoorsTek (U.S.), Corning (U.S.), Honeywell (U.S.), Hexcel (U.S.), and Kyocera (Germany).

Chapter 3

Industry Trends and Opportunities

Chapter 3: Industry Trends and Opportunities

This chapter examines industry supply networks, significant industry organizations, and the trends in market dynamics and values for aerospace materials.

Value Chain

Along with their material composition, aerospace materials have a distinct upstream supply chain. Ceramics or composites are used in these materials. Materials that are solely metal-based, for example, require distinct source materials (and hence require separate upstream supply networks). There is also a significant disparity in end consumers. The selling process drastically changes from client-to-client. For instance, the selling process for the defense projects run by the government is different from that with the civil aviation companies.

Mineral Mining for Metals/Alloy Production

This category involved the extraction of ore-containing minerals from the earth. Large businesses mine major components such as nickel, cobalt, aluminum, titanium, and iron all over the world. BHP Billions Ltd., Rio Tinto, Fortescue Metals Group, Vale SA, MMC Norilsk Nickel, Jinchuan Group, Xstrata Plc, Freeport Cobalt, Glencore, and Umicore are among the major players. Large mining firms or specialist companies that target rare or small-volume metals may mine or separate other metals and alloy components as components of an ore targeted for another metal, or they will be independently mined.

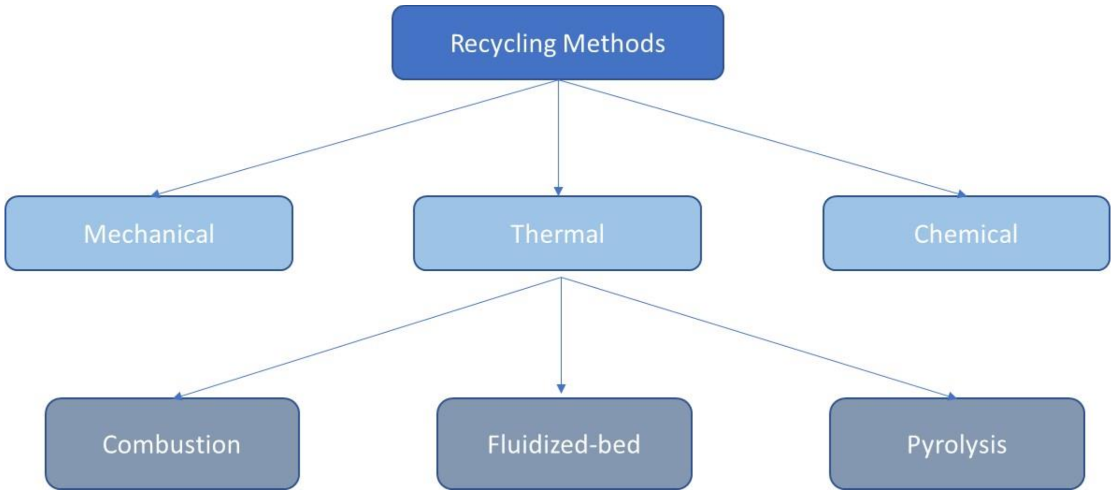
Initial cleaning and separation processes are included in mineral extraction and mining to eliminate contaminants from the produced ore and minimize the volume of rejects carried to the next stage in the supply chain.

Material Recyclers

Alloys, like metals, are highly recyclable, but recycling certain alloys is more difficult than recycling other forms of scrap metal. If recycled, alloys can be used once again. Non-target metals and other chemicals must be removed from recycled material before it can be used. The resultant materials are then injected into the metals/alloy supply chain, with metals often being recovered for purification and eventual reuse.

For composites, the recycling methods are as shown in the following figure:

Figure 1
Composite Recycling Processes



Source: Composite Material Recycling Technology—State-of-the-Art and Sustainable Development for the 2020s

The mechanical recycling process includes cutting the composite waste into small parts, while separating it from the structure. The thermal recycling of composites focuses on controlled combustion of composites to recover material with minimum damage possible. The chemical recycling process includes the conversion of polymers to monomers or partial depolymerization to oligomers as a result of chemical reaction. The polymer matrix in the waste composite is broken down by dissolving it in chemicals such as acids, bases and solvents. This method is mainly used for carbon-fiber reinforced polymer (CFRP).

Table 1
CFRP and Glass Fiber Recycling Process and Retained Tensile Strength

CFRP Recycling	Retained Tensile Strength
Mechanical	~50%*
Fluidized-bed process	~75%
Pyrolysis	36–93%; typically, ~80% or less
Microwave-assisted pyrolysis	~80%
Chemical	90–98%; typically, ~95% or less
High-voltage fragmentation	~83%**
Glass Fiber Recycling	**Retained Tensile Strength**
Mechanical	~78%
Fluidized-bed process	~50%
Pyrolysis	~52%
Microwave-assisted pyrolysis	~52%
Chemical	~58%
High-voltage fragmentation	~88%

Source: Journal Composite Science 2021

Raw Materials Producers
Producers of raw materials take raw materials from the ground or create raw materials in various ways for the manufacture of new aeronautical materials. The minerals and ceramics basic materials utilized in composites and ceramics are the subject of this section. Mining and extraction of the mineral elements needed in the manufacturing of aeronautical materials are common operations. Producers of raw materials also create base materials for other sectors, such as ceramics, glass, and fiberglass, as well as other critical raw materials required for a range of end applications. It's worth noting that certain raw materials companies put a strong emphasis on recycling and recovering target materials from discarded or squandered resources. Raw materials producers operate in a commodities market, thus to some degree that standard prices can be calculated, within a margin of error.

Petroleum Supply Chain
All upstream oil extraction and recovery, as well as transportation of crude oil, natural gas and other raw petroleum products to centralized refineries, storage and other raw natural resources management infrastructure and components are all part of the petroleum supply chain. The petroleum supply chain is a vital part of the resin and plastic manufacturing process, which includes resins and plastics used in aircraft composites. Furthermore, many types of petrochemicals serve as foundation materials for developing aircraft materials. The petroleum supply chain is completely commodified, and it is influenced by global geopolitical forces as well as conventional supply and demand factors.

Ore Concentration and Metal Extraction
Metals required for super alloy manufacturing are removed from their ore after mining. Depending on the metal and the characteristics and composition of the base material, the extraction process can take a variety of shapes. Compound ores are common in incoming ores, which implies that different metals may coexist in the same base rock. Cobalt, copper and nickel, for example, are frequently found combined in extracted ore. The ore body is crushed or pulverized during the concentration process, and then separated depending on an ore's specific gravity. This is generally done in water, with heavier target particles sinking first and lighter fines being discharged as tailings. Following concentration, the extraction process may entail further crushing or pulverizing, as well as heat and chemicals, to separate the target metal(s) from the surrounding rock. Other methods include electrorefining or direct smelting without the use of any chemicals. The ore concentration process can be done at the mine site, but the metal extraction procedure is usually done elsewhere. Depending on the target metal and local supply chain variations and features, concentration and extraction may be accomplished by the same business or by distinct companies.

Intermediate Materials Producers
Intermediate materials producers frequently overlap with metal extractors. These producers coarsely remove impurities from extracted metals, such that the resulting material might be considered low purity aluminum, nickel, iron, or cobalt, or other metals or blends of metals with some level of residual contamination. However, some impurities remain in these materials in varying quantities.

Metal Refineries
Metal refineries are where entering metals are purified into single metals. Various metals may be refined in refineries for limited volume, while higher-value metals are utilized in advanced alloy manufacturing. These include those required for super alloys. Large-scale metal refineries, such as those for aluminum, iron or nickel, may have dedicated facilities for these materials. In order to facilitate transportation to various metal refineries, metal refineries typically generate billets, ingots or other forms of their target metal. Metal refineries are also known as raw materials producers in product-oriented supply chains.

Petrochemical Producers
Petrochemical producers include refiners and facilities downstream of the refining process that convert base/raw crude oil and other natural energy extractables into base chemicals and preliminary products. Petrochemical producers generate base materials, often through steam cracking and reforming, such as olefins (ethylene, propylene and butane), aromatics such as benzene, toluene and xylenes, and other chemicals. Petrochemical producers are also responsible for some of the base materials that are used by downstream chemical producers to manufacture and synthesize aerospace materials including composites.

Intermediary Metallurgists/Forgers
This supply chain phase may be incorporated into specialized equipment or components manufacturers, as well as metal refiners in some circumstances, although it is not generally integrated into original equipment manufacturers (OEMs). Intermediary metallurgists follow a computer-guided procedure that includes one or more super alloy manufacturing processes. Intermediary metallurgists and forgers usually finish their advanced alloy process by shaping the metals into billets or other conventional shapes for transportation and delivery.

Aerospace Materials Manufacturers
Materials from the metals, petroleum and/or raw materials supply chains (including ceramics) are combined for the manufacture of basic materials utilized in the aerospace sector in this supply chain phase. This category can be up-or-down-integrated with other supply chain components, or it can be a stand-alone element for practical purposes.

Parts Manufacturers
Component makers' main job is to turn raw aeronautical materials into functional parts, which can be done in a variety of ways. Manufacturers of parts may be physically distinct from the supply chain stages mentioned below, or they may work in tandem with intermediary metallurgists. They employ methods congruent with resin, composite and ceramic components production, as well as forgers or equipment makers. Manufacturers of target parts and other equipment components may employ powder metallurgy or other casting processes for alloys.

OEMs
OEMs mix basic materials accessible from upstream supply chain elements with other parts available from other fabricators to create components utilized by specialist equipment makers or product manufacturers. Most OEMs create auxiliary equipment such as motors, pumps and actuators, rather than equipment that directly employs super alloys, in the context of superalloys. OEMs may create goods that downstream chain members may readily brand.

Whether or not intermediate rebranding occurs, a single OEM in the superalloy supply chain plays an important role in the fabrication of the fundamental functioning parts utilized in many types of aerospace applications. Typically, OEM selection is influenced by a mix of price and delivery schedule, especially when a number of prospective vendors meet minimum/adequate production criteria.

Specialty Equipment Manufacturers
Specialty equipment manufacturers create specialist components for superalloy product lines. They have patents in their field of expertise. Some of the major specialist equipment manufacturers may also have overlap with companies in the midstream supply chain. Smaller equipment manufacturers focus on a single product line, relying on OEMs or other specialist equipment manufacturers to supply non-specialized components such as motors, actuators, pumps, gauges, and pipes. Many key functional components of equipment that uses sophisticated aircraft materials are manufactured by specialty equipment manufacturers. The quality and reliability of final goods are heavily reliant on the quality of these producers' products.

Product Manufacturers
In the aerospace sector, product manufacturers play a complementary function to specialist equipment makers. They may rely on sophisticated materials to assist their manufacturing process, but the end goods that they produce under their business model may not be specifically specialized to be utilized just in the aerospace sector. When creating fire extinguishers for commercial jets, for example, a producer of fire extinguishers for the aerospace sector may rely on innovative lightweight materials. However, they may also make non-advanced materials fire extinguishers for use in other sectors.

End Users
The final owners or operators of a finished, produced product or system using advanced aeronautical materials are known as end users. End users are generally responsible for the final product's operation and use, including maintenance. This is common in the commercial airplane industry, where airlines typically manage their own maintenance process, as well as in the defense industry, though the defense industry may also rely on specialized contractors to fulfil these roles.

Industry and Key Research Organizations

Globally, there are a number of industry organizations focused on developing new materials for the aerospace industry. These include component manufacturers along with others involved in the production and deployment of the technologies and applications under consideration in this study. Manufacturers, researchers, developers, standards developers, and others are all supported by the industry organizations. These organizations are important to the industry as they facilitate information sharing and the development of technical expertise, provide training, and engage in lobbying activities. They also design legal and industrial manufacturing guidelines and standards. Manufacturing and product development data is also collected by some industry organizations, which they may share with their members.

The following table summarizes the key global industry organizations as well as a few scientific organizations.

Table 2
Key Global Research Organizations in the Aerospace Ceramics Industry

Organization	Region	Description
European Foundry Association	Europe	The European Foundry Association (CAEF) was established in 1953 and serves as an umbrella organization for the European foundry industry. The organization supports its members by managing industry interests considering economic, legal, technical, and social issues and concerns. The organization's membership includes each of the national foundry organizations from a total of 22 European countries. CAEF is headquartered in Dusseldorf, Germany, and distributes various types of data and information including ferrous and non-ferrous foundry production data, along with employment data for those foundries on an annual basis. To its members, the organization provides additional information regarding industry-specific verticals and processes, including automotive casting, wind turbine casting, continuous casting, the steel casings industry, and general engineering, among others.
European Investment Casters' Foundation	Europe	The European Investment Casters' Foundation maintains various members across Western Europe, but also in the U.S., Australia, India, Indonesia, and Tunisia. Members include those directly involved in the European foundry industry, including industry participants, consultancy services, research institutes, suppliers, and tool makers. It sponsors conference and technical workshops, and publishes the Foundry Trade Journal Co. and Castings Buyers Guide. It has shared activities with the U.S. Investment Casting Institute and the Cast Metals Federation.

Organization	Region	Description
Plastics Europe	Europe	Plastics Europe is a leading pan-European association and represents plastics manufacture active in the European plastics industry. The plastics industry in Europe is a vibrant sector that helps improve the quality of life by enabling innovation, facilitating resource efficiency and enhancing climate protection. In addition to the plastics manufacturers represented by Plastics Europe, the plastics industry includes converters, represented by European Plastics Converters (EuPC), recyclers, represented by European Plastic Recyclers (PRE), and machine manufactures, represented by European Plastic and Rubber Machinery (EUROMAP). Plastics Europe is a leading European trade association, with centers in Brussels, Frankfurt, London, Madrid, Milan, and Paris. The organization networks with European and national plastic associations and has more than 100 member companies that are responsible for producing more than 90% of all polymers across the 28-member states of the European Union, plus Norway, Switzerland and Turkey. On a global level, Plastics Europe actively supports the World Plastic Council (WPC) and Global Plastic Alliance (GPA).
GKV-General Association of German Plastic Processing Industry	Germany	The GKV is the umbrella organization of the German plastics processing industry. It represents the shared interests of the around 700 companies (plastic packaging, plastic end-consumer, performance plastics, and rein-forced plastic industries).
VDMA-German Engineering Association	Germany	The VDMA represents the interests of over 200 member companies in Germany. Members receive, among other services, support in the form of global market information in the mechanical engineering client industry sectors.
ASM International	Global	ASM International, formerly known as the American Society of Metals, is the world's largest association of materials-centric engineers and scientists and seeks to educate and connect the materials community to solve problems and to stimulate innovation around the world. The organization is the longest-established materials information society, seeking to connect its members through a global network of peers alongside access to trusted materials information through a combination of content and data, education courses, international events, and research. ASM provides information to help predict the behavior of the materials and to help overcome design challenges, and aids in transfer of knowledge to help achieve superior materials related to product performance. It provides technical guides and publishes the journal Super Alloys.
Cobalt Development Institute (CDI)	Global	The CDI is a non-profit trade association composed of producers, users, recyclers, and traders of cobalt. The organization promotes the sustainable and responsible production and use of cobalt in all its forms. The organization seeks to act as a knowledge center for governments, agencies, industry, the media, and the public on all matters concerning cobalt and cobalt-containing substance, including health, safety and environmental issues.
International Chromium Development Association (ICDA)	Global	The ICDA functions as the international association of the chromium industry. Its members represent 26 countries across five contents. Based in Paris, France, the association was created in 1984 as a non-profit association. The organization's members include producers of chromate ore and many users of chromite, including producers of ferrochrome, stainless steel, chromium metal, chromium chemicals, refectory bricks

Organization	Region	Description
		and foundry sands, trading companies, end users and service providers. The ICDA's purpose and objective are to promote free competition and to provide benefit to consumers of chromium.
International Nickel Study Group (INSG)	Global	The INSG operates as an autonomous, intergovernmental organization located in Lisbon, Portugal. The organization was established in 1990; its members consist of nickel-producing, -using and -trading countries. The INSG is not involved in market stabilization activities or market intervention of any kind. The primary objectives of the organization are to: collect and publish statistics on nickel markets, including production, consumption, trade, stocks, and prices and recycling; publish data on industry facilities and environmental regulations; provide a forum for discussions on nickel issues; and perform economic analyses of nickel markets and related topics.
Metal Powder Industrial Foundation (MPIF)	Global	The MPIF comprises six individual trade associations representing various aspects of powder metallurgy, metal powders and particulate materials. The MPIF focuses on promoting and helping to deploy powder metallurgy. It provides its member companies with services that help to advance powder metallurgy while seeking to promote technological benefits to prospective end users.
Nickel Institute	Global	The Nickel Institute is a global association of the world's primary nickel producers, which collectively account for roughly 85% of worldwide annual nickel production outside of China. The Nickel Institute grows and supports markets for new and existing nickel applications, including stainless steel. It also promotes sound science, risk management, and socio-economic benefits as the basis for public policy and regulation. Through its science division, Nickel Producers Environmental research Association (NiPERA), the institute also conducts scientific research relevant to human health and the environment and nickel as a material. The organization maintains offices in Asia-Pacific, Europe and North America.
Society of Plastics Engineers	Global	The organization operates and has members in 84 countries, with more than 22,500 members globally. The organization seeks to unite plastic industry professionals worldwide helping them succeed and strengthening their skills through networking, events, training, and knowledge sharing. The organization supports the industry across its full value chain, from scientists, to engineers, technical personnel, and senior executive, also irrespective of education level, gender, culture or age. The organization focuses strongly on helping its members to meet personal and professional goals. The organization seeks to be responsible also for making the plastics industry better by providing a forum that generates a strong awareness of issues facing the plastics company, to help identify solutions that will benefit everyone.
The Minerals, Metals, and Materials Society (TMS)	Global	The TMS is headquartered in the U.S. but maintains an international focus in both its membership and its activities. TMS has a relatively broad scope, encompassing a wide range of materials and engineering. Aspects of the materials industry represented include materials processing, and primary metals production, basic research and advanced materials applications.
E-Foundry	India	E-Foundry seeks to serve educators and industry professionals with information about metal casting and manufacturing. The organization

Organization	Region	Description
		seeks to empower teachers in engineering and polytechnic institutes to enhance the interest and employability of students in metal casting, which it views as a key facet of the country's manufacturing sector. The organization is directly supported by the National Knowledge Network mission of Government of India, New Delhi, and provides educational content that is largely derived from courses and R&D projects at the Indian Institute of Technology in Bombay. E-Foundry offers an online simulation laboratory with 3-D modeling capabilities and an alloy database, information on casting processes, a library of information on alloys and their casting, and model simulation cases.
National Metallurgical Laboratory	India	The National Metallurgical Laboratory is the third in India's Council of Scientific and Industrial Research (CSIR) family of 38 laboratories. The organization was founded in 1946, and the laboratory was formally inaugurated in 1950. The lab was part of what was at that time termed India's Great Plan, for providing India with a network of research institutes capable of moving the country forward in science and technology. Today, the laboratory remains nationally run and oversees a range of R&D. Its divisions include applied chemistry and corrosion, business development and monitoring, engineering, materials science and technology, metal extraction and forming, and mineral processing. The organization also maintains four centers for analytical chemistry, information management and dissemination, calibration, and non-destructive evaluation.
Canadian Institute of Mining, Metallurgy and Petroleum (CIM)	North America	CIM was founded in 1898 and is the leading non-profit technical society of professionals in the Canadian minerals, metals, materials, and energy industries. The organization has three goals: to create, curate and deliver leading-edge knowledge; to foster a connected and engaged CIM community; and to expand awareness of the contribution mining makes to society. The organization has over 14,000 members, which represent industry, academia and government. CIM consists of 10 technical societies and over 35 individual branches.
Forging Industry Association (FIA)	North America	The FIA is focused on metals forging. It provides support and services to its members in industry benchmarking (orders and shipments, profits, safety and compensation; global networking, through meetings, an annual Forge Fair and technical conferences; training and education, including on-line Forging University, manufacturing workshops and business seminars. The FIA also provides public policy advocacy, including a political action committee (PAC). It also drives demand for North American forgings through electronic customer RFQs and by educating customers of the value of designing with forgings. It also is engaged in the development and transfer of technologies, including leveraging industry and government resources for R&D.
North American Die Casting Association (NADCA)	North America	The North American Die Casting Association (NADCA) was founded in 1989 at the time of the merger between the American Die Casting Institute (ADCI) founded in 1928, and the Society of Die Casting Engineers (SDCE) founded in 1957. The organization seeks to increase and promote industry awareness, as well as domestic growth in the global marketplace, and member exposure. Based in Arlington Heights, Illinois, the organization includes a combination of individual and corporate members located across the U.S., Canada and Mexico. The NADCA provides an array of support mechanisms to its members and to the die

Organization	Region	Description
		casting industry in general. The organization presents its members with monthly magazines and e-Newsletters designed to keep them up to date on industry events and technical updates. The organization also provides die casting design assistance, discounts on publications and services, access to sales leads, and enhanced exposure to OEMs. Recently, the organization completed a searchable die caster database, which contains over 500 domestic die casters. This database can be sorted by name, region, materials, and casting sizes. More generally, the organization is heavily involved in R&D efforts while seeking to expand funding sources and dispel myths associated with die casting techniques. Other facets of NADCA's program include outreach through meetings and expositions, education, design assistance, government affairs and advocacy, chapter relations, and research and industry related updates for members and the public at large.
Foundry Equipment and Supplies association (FESA)	United Kingdom	FESA was initiated almost 100 years ago to promote quality in foundry equipment, technology, knowledge, and materials. FESA works with the U.K.'s foundries to ensure that they remain at the forefront of their technology, and practice and implementation. FESA members now provide this service to the global cast metals industry. FESA hosts several annual gatherings that include the World Foundry Organization Technical Forum, the World Foundry Congress, the International Foundry Forum and Ankiros.
Institute of Materials, Minerals and Mining (IOM3)	United Kingdom	IOM3 is an engineering-based industry organization based in the U.K. Its activities encompass the entire materials cycle, from exploration and extraction, through characterization, processing, forming, finishing and application, to product recycling and land reuse. The organization seeks to promote and develop all aspects of materials science and engineering, geology, mining and associated technologies, mineral and petroleum engineering and extraction metallurgy.
American Chemical Society (ACS)	United States	A self-governed individual membership organization that consists of more than 159,000 members at all degree levels and in all fields of chemistry. The organization provides a broad range of opportunities for peer interaction and career development, regardless of professional or scientific interests. The programs and activities conducted by ACS today are the products of a tradition of excellence in meeting member needs those dates from the Society’s founding in 1876.
American Chemistry Council	United States	The American Chemistry Council (ACC) represents a diverse set of companies engaged in the primary business of chemicals representing a $550 billion industry. The organization seeks to solve major challenges relevant to the industry in the U.S. and globally. The organization's stated mission is to deliver value to its members through advocacy, using best-in-class member engagement, political advocacy, communications, and scientific research. The organization is committed to fostering progress in our economy, environment and society. The organization supports various chemistry-oriented industries, including plastics as well as chemical production. and various others.
American Foundry Society and Institute (AFS)	United States	AFS is a non-profit association that serves members of the metal casting supply chain worldwide. AFS was founded in 1896 and has 800 corporate members and 7,500 individual members that represent metal casting suppliers and OEM facilities in 41 countries, covering all metal casting processes and materials, AFS provides members with advocacy efforts in

Organization	Region	Description
		Washington, D.C., along with technical education. AFS supports the transfer of research and technology from researchers to the metallurgy and metal casting industry, suppliers and buyers of castings. Examples include vacuum-assisted casting, counter gravity for investment casting, V processes and vacuum melting. AFS members function within three markets: metal casting and production of metal cast parts; metal casting suppliers; and casting buyers or OEMs. AFS has 81 student and professional chapters throughout North America. The AFS Division Council works to develop and transfer research and technology to the metal casting industry.
American Institute of Aeronautics and Astronautics (AIAA)	United States	AIAA was founded in 1962 and has over 30,000 individual members from 88 countries alongside 95 corporate members. It is the largest technical society dedicated to the global aerospace profession. AIAA's stated mission is to advance the future of aerospace for the benefit of humanity. AIAA provides outreach to its members through technical publications, journals and reports; career enhancement and development activities; public policy support that encompasses state and federal advocacy and lobbying, development of policy papers, testimony and speeches and identification of key issues; and conferences, courses, workshops, and forums.
American Mold Builders Association	United States	Established in 1973, the American Mold Builders Association (AMBA) is the largest grassroots organization in the U.S. dedicated solely to the mold manufacturing industry. As a national nonprofit trade association serving over 200 member companies and over 50 partner companies (supplier members), AMBA provides its members with access to the most powerful networking in the industry. AMBA is driven by a Board of Directors made up of owners and presidents of leading mold manufacturing companies. Having over 1,000 industry professionals involved in the organization provides a variety of channels to expedite solutions and build momentum for continued growth and development in areas that will positively impact the mold manufacturing industry.
American Society of Mechanical Engineers (ASME)	United States	Founded in 1880, ASME is a nonprofit membership organization that supports collaboration, knowledge sharing, career enrichment, and skills development across all engineering disciplines. ASME has 130,000 members in 151 countries. About 30% of its members are students. ASME maintains standards for engineering certifications. Publications include journals that focus on advanced materials and alloys/superalloys, such as the Journal of Engineering Materials and Technology.
Investment Casting Institute	United States	The Investment Casting Institute is based in the U.S. and primarily serves the casting industry for that country, although it increasingly includes international industry participants from Europe, Asia-Pacific and Australia. The organization produces several types of publications, including the Investment Casting Handbook, INCAST- the official magazine of the Investment Casting Institute, as well as various CDs, booklets, books, case studies, and other media. The organization maintains several types of annual events, which include industry certification courses, an annual technical conference and exposition, and its annual World Conference on Investment Casting and Equipment Exposition.
Plastic Pioneers Association	United States	The Plastics Pioneer's Association is an organization of individuals who are persons of accomplishment in the industry. The organization

Organization	Region	Description
		supports scholarships, educational programs, a history center, and more to engage the next generation of people in the world of plastics. The organization celebrated its 70th anniversary in 2018. The organization offers educational grants and scholarships that help students pursuing careers in the various fields of plastics and materials science. Through monetary donations, the organization helps to maintain the National Plastics Center at Syracuse University. The organization contributes to educational support programs such as the Plastivan, which caters to school-age children.
Society for Mining, Metallurgy and Exploration (SME)	United States	SME has 15,000 members in more than 100 countries representing all categories of professionals who serve the minerals industry, including engineers, geologists, metallurgists, educators, students, and researchers. The organization also seeks to advance the worldwide mining and underground construction community through information exchange and professional development. SME is based in Englewood, Colo.
The Aluminum Association	United States	The Aluminum Association serves as the aluminum industry's lobbying voice at the federal level in the U.S. The association is committed to advancing aluminum as a sustainable metal of choice. It focuses on areas outside of super alloys, which comprise a small portion of the overall aluminum market. The association provides timely industry statistics and information on emerging issues; creates, maintains and advocates for standards and technical documents that encourage the use of aluminum; advances regulatory and legislative policy in state, federal and international arenas; and convenes forums on emerging issues.

Source: BCC Research

Key Market Opportunities

The following section summarizes key market opportunities in the global aerospace ceramics market.

Global Airplane Industry Trends

Commercial air carriers, particularly those in the U.S., have historically followed patterns of boom-bust cycles. These were caused by volatility that was once considered to be foundational to the industry, where major and ongoing capital investments were needed to maintain working aircraft. Meanwhile, competition continued downward pressure on prices and revenue, leaving major air carriers strapped for cash during lean periods. However, a significant change occurred in the industry during the 2007 global economic turndown. At that time, profitability crashed in an unprecedented manner, as demand for air travel dropped, which led to a period of reorganization for the U.S. and global airline industry. Many consumers will recall a time of standard in-flight meals, more direct routes and planes flying below passenger capacity.

That era ended during the recovery years, and airlines substantially revised their operational procedures, minimizing losses by lowering operating costs, reducing and eliminating unprofitable routes, and reducing reliance on older, less fuel-efficient aircraft. Significant mergers also took place, and flights suddenly became full, rather than having many open seats. Similar changes have taken place in commercial cargo markets, although these have focused on route optimization, consolidating lower profitability routes, and investing in planes with higher fuel efficiency and advanced technology.

In the wake of those industry-level changes, the U.S. and global airline industries had significantly transitioned their operating structure to support more consistent profitability. Many global air carriers maintained profitable operation following their restructuring efforts in the wake of that global economic turndown. Industry analysts forecast stable profitability for the foreseeable future, which was generally anticipated until the onset of COVID-19.

COVID-19 has injected instability into the system and is expected to result in a temporary crash in travel demand that will last 12 to 24 months. As a result, airlines will be less able to invest in new equipment, and purchase of new planes will likely be greatly reduced until 2022 or even 2023. In addition, economic restructuring will likely result in reduced travel demand. As a result, we expect to see a slowing of markets. In comparison to the intermediary period between the global economic turndown and the onset of COVID-19 the industry could see significant restructuring as a growing number of would be travelers have sought to reduce their reliance on traditional in-person meetings that require travel, particularly in the business sector.

Efficiency and Fuel Cost

Today’s commercial aircraft are more efficient than ever, leveraging continual advances in superalloy technology. Today’s jet turbines can burn hotter and more efficiently than their predecessors. This shift to hotter burning engines has helped to drive continued R&D in the superalloy industry while contributing to greater demand for advanced and aerospace materials such as ceramics and composites. Silicon carbide (SiC) is currently in enjoying the limelight from engine manufacturers for its applications in hot engine sections. Fuel efficiency is also a growing consideration for military applications where improved efficiency can mean longer mission times and reduced refueling requirements.

When the global economic turndown struck, commercial passenger and cargo airlines were struck especially hard by reduced demand for passenger and cargo flights, and historically high fuel prices. In 2008, in perhaps the deepest part of the global economic turndown, fuel prices hit an all-time high that still has not been exceeded. Oil prices reached $155 per barrel in June 2008, then fluctuated between $85 and $115 through July 2014; this marked a significant increase from the oil prices of around $30 to $45 per barrel through most of the 1990s through 2004. A three-to-four-fold cost in fuel was especially difficult to bear in conjunction with reduced demand for air travel during the turndown. Ridership per plane fell off dramatically. Airlines were paying excessively high fuel prices to run flights with more seats than passengers, making profitability exceptionally difficult.

In contrast, during the post-COVID economic restrictions, fuel prices dropped significantly and economic pressure to reduce fuel consumption and improve efficiency was, at least temporarily, lifted. Nonetheless, greenhouse gas (GHG) emission restrictions and goals have continued to drive demand for fuel efficiency, even without the same cost pressure on fuel.

Prior to COVID-19, the industry had been in a period of replacing airplanes with more fuel-efficient models. As discussed above, the global airline industry balanced its new strategies successfully by using a number of factors; part of the airlines' plan was to consolidate less profitable routes. The other part of their approach, which benefitted airplane manufacturers and supported aircraft demand for superalloys centered on increasing fuel efficiency. Only limited gains in fuel efficiency can be achieved by updating older technologies with new components. These may drive low single-digit percentage reductions in fuel costs. For more substantial improvements in fuel efficiency, whole system upgrades, that is, airplane replacement, were needed. The industry responded accordingly, resulting in an uptick in demand for high-efficiency planes. The industry has strived to meet that demand. Now, despite reduced purchases, commercial air carriers are still looking for efficient systems.

Generally, improved efficiency comes through improved engine efficiency and reduced weight. At this point, jet engines are largely quite efficient, and updates using available technologies result in small incremental gains. Weight reduction, known as lightweighting, is therefore the primary frontier for improving fuel efficiency in planes. Lightweighting is a significant driver for the use of aerospace ceramics and composites in airplanes. These materials are stronger, with reduced weight profiles and improved performance, in comparison to conventional technologies. In fact, lightweighting continues to be the primary driver of advanced material incorporation into the global airplane industry. While market fundamentals in the airplane manufacturing industry are likely to see increased variability in the coming months and years, we expect to see a strong and continued push toward increased lightweighting.

Rotary/Helicopter Markets

The markets for advanced materials for helicopter/rotary applications are strongly dependent on helicopter-related market demand factors. To this end, the commercial helicopter market is disparate from commercial passenger and cargo aircraft markets and is driven by wholly different global market trends and influencing factors.

Large segments of the global helicopter market are supported by offshore industrial operations, particularly operations relating to the oil and gas industries. After a period of relatively high demand for offshore explanation and development when oil prices were high, the July 2014 drop in oil prices brought that surge in demand to a crash. Lower prices are founded on increased global oil supplies, especially in North America, combined with slower than expected economic performance in many parts of the world, including Asia-Pacific and Europe. While recent OPEC actions to reduce the supply have buoyed oil prices marginally, they are not yet at a point where additional exploration and development of costly offshore resources are economically viable. Offshore demand for helicopters is expected to continue to slide for the next several years, as existing projects wind down, with a slow replacement rate consistent with challenging offshore development and operations economics. Offshore operations continued to sputter for the following several years before the oil price crash of 2020 greatly reduced offshore profitability.

The industry has also suffered increased safety-related scrutiny in recent years. Several well-publicized helicopter failures and crashes resulted in fatalities, which has left helicopter OEMs struggling to shore up safety-related issues, along with their reputations.

The decreased offshore demand was compensated to a small extent by increased demand for onshore applications in civil deployments including emergency medical service (EMS), as well as perhaps police or surveillance. Select EMS markets have seen growth, notably in Asia-Pacific, where industry growth has been in the low- to mid-single digits. Nonetheless, these numbers are restricted in scope, and key prospective markets like China continue to be hampered by airspace restrictions that limit civil helicopter activity and utilization, thereby impacting the ceramics markets.

Another key factor influencing the market is a lack of demand for replacement. Lower-flying helicopters, unlike aircraft, are not generally pressurized and are not subject to the same stress cycles. As a result, an old helicopter may be rebuilt several times by the manufacturer and restored to duty as refurbished. Fuel economy is what drives replacement components for helicopters that see a lot of use. Fuel economy is closely related to carbon emissions, which are subject to increasingly strict controls across the world, but particularly in European markets. Fuel costs also promote fuel efficiency-related replacement for highly utilized helicopters; however, the strength of this demand has waned since mid-2014 as fuel prices have moderated. Fuel costs are also less of a concern for helicopters that are only used sometimes, such as those used by police and EMS.

Military Markets

Government allocations drive the global military markets for aerospace equipment. These can change as a result of leadership changes, shifting leadership priorities, and shifting global security conditions. Spending on military jets in the United States, which is by far the largest contributor to global defense spending, was steady from 2013 to 2016, with a 1% to 3% increase or decline year on year. Then, during the Trump administration, spending skyrocketed. Other countries, particularly China, have increased military spending, however much of this has occurred outside of the aerospace industry.

Advances in military spending in the U.S. budget advanced under Trump. However, it is expected that U.S. spending will fall as a percentage of total global military spending in the long run. This will be due to increased military spending abroad, particularly by China, which has already significantly raised its military budget and will most likely maintain or further expand (and maybe greatly enlarge) that budget in the near- to mid-term. This could shift military markets for jet engines toward China, although based on current development rates and public planning, major shifts are not expected during the five-year forecast period. However, the impact of such spending on outside markets remains unclear. China has now set up its own state-run aircraft engine maker, which may see the bulk of China's market value in the future, assuming that it can get its engines off the ground.

Space Industry

As enterprises, governments, and, increasingly, investors look to the future, the space industry has achieved unprecedented visibility. Over the next two decades, global leaders such as SpaceX, Boeing, Virgin, and numerous worldwide government-funded programs are likely to display a considerable interest in space. Currently, however, despite tremendous innovation, commercial volumes remain small, only a tenth of that of the commercial airplane sector. Furthermore, currently existing space industry equipment is built on a piece-by-piece basis by only a few companies. This equipment is not mass-produced. As a result, while many new and technologically intriguing breakthroughs are emerging from the industry, and more are sure to follow, markets are not yet ready. We do not expect a big increase in global space industry market volume for at least three to five years.

Development of New Aerospace Materials

The industry is focusing on R&D efforts relevant to new aircraft materials on a macro level, especially on patents. There is a substantial and ongoing interest in the development of novel developing aerospace materials. As a result, companies in this business have been working hard to invest in and then produce new, more specialized, and advanced materials for a wide range of end customers. One of the key goals of this process is to shift more end goods and components of end products away from other materials and toward plastics and composites. In comparison to metal and ceramics, for example, plastics and composites provide several advantages, and improvements in plastics additive technology are helping to extend composites markets and applications in ways that were previously unattainable.

Chapter 4

Market Breakdown by Composition

Chapter 4: Market Breakdown by Composition

In this report, aerospace ceramics are segmented based on their chemistry as oxides, non-oxides, ceramic composites, and glass ceramics. The oxides include aluminum oxide (alumina), silicon oxide (SiO_2) and zirconia (ZrO_2), while non-oxides refer to borides, nitrides and carbides etc. Composites of ceramics can be formed with a combination of oxides or non-oxides, along with metal and polymer components. The materials for a composite are selected based on the target application of the composite. This gives composites a leading edge over other materials.

The technical advancements in the ceramics industry have helped aerospace applications through development of new categories of ceramics called high temperature ceramics (HTC) and ultra-high temperature ceramics. These ceramic compounds are known for their ability to withstand temperatures even above 3,000°C.

Table 3
Global Market for Aerospace Ceramics, by Composition, Through 2026
($ Millions)

Composition	2020	2021	2026	CAGR% 2021–2026
Oxide	706.3	727.5	906.6	4.5
Non-oxide	423.8	449.2	589.9	5.6
Composites	3,578.6	3,774.0	7,312.1	14.1
Total	4,708.7	4,950.7	8,808.5	12.2

Source: BCC Research

Table 4
Properties of Some Key Ceramics

Ceramic	Melting point (°C)	Density (g/cm^3)	Strength (MPa)	CTE ($\times 10^{-6}$/°C)	TC (W/m.K)	Elastic Modulus (GPa)
Beryllium oxide	2530	3.1	246	7.4	210	400
Alumina	2050	4.0	455	8	40	380
Zirconia	2700	5.6	175	10.5	19	140
Aluminum nitride	1900	3.3	441	4.4	180	320
Silicon nitride	1900	3.2	210	3	17	175
Boron carbide	2350	2.5	350	4.3	25	450
Silicon carbide	2700	3.2	140	4.3	50	210

CTE= coefficient of thermal expansion, TC= thermal conductivity, MPa= megapascal, GPa = gigapascal

Source: TWI Ltd.

Oxides

Oxide ceramics are compounds of oxygen and metallic or metalloid elements. The common metallic components are aluminum, zirconium, titanium, and magnesium, while silicon is the most widely used metalloid component in the oxide ceramics. These materials have a range of electrical properties and high melting points with low wear resistance. Among the oxide ceramics, alumina and zirconia are the most popular ceramics in aerospace industry.

Alumina

Alumina ceramics (Al_2O_3), also known as aluminum oxide ceramics, are mostly manufactured applying the Bayer process on bauxite. The Bayer process takes place in four steps which involve use of caustic soda at high temperatures. The process yields alumina in form of hard white powder.

Alumina ceramics show high electrical insulation, thermal stability, flexural strength, and hardness along with wear resistance and corrosion resistance. These ceramics are the most widely used ceramics among the technical ceramics. Alumina supports different manufacturing processes such as uniaxial (die) pressing, slip casting, isostatic pressing, injection molding, and extrusion. More options to shape alumina make it easier for component manufacturers to cater to demand for a variety of components.

These ceramics primarily cater to the demand for ceramics in electrical applications in the aerospace industry. Alumina is used to manufacture products such as resistors, capacitors and sensors, which need to maintain their performance even at high temperatures. It is also used as a key component in various ceramic composites used in other applications such as thermal barrier coatings (TBC) and thermal protection systems (TPS). However, due to its low thermal shock resistance and low toughness these ceramics cannot sustain instant changes in temperature. Thus, alumina ceramics are mostly used in combinations with other ceramics or materials in thermal applications.

A typical range of purity available in alumina ranges from 75% to 99.9%. Following are some of the properties for alumina in various purities from 74% to 99.96%.

Table 5
Properties of Alumina, by Purity

Property	ASTM Method	Units	AL74 74%	AL95 95%	AL96 96%	AL98 98%	AL995 99.5%	AL9980 99.8%	AL9996 99.96%
General									
Crystal size (average)	Thin section	Microns	13	11	8	7	6	6	2
Color	–	–	White	Ivory	White or purple	White	Ivory/white	Ivory	Off-white/blush
Gas permeability	–	Atm cc/sec	Gas tight $<10^{-10}$	Gas tight $<10^{-10}$	Gas tight $<10^{-10}$	Gas tight $<10^{-10}$	Gas tight $<10^{-10}$	Gas tight $<10^{-10}$	Gas tight $<10^{-10}$
Water absorption	C 20-97	%	0	0	0	0	0	0	0
Mechanical									
Density	C 20-97	G/Cc	3.03	3.65	3.71	3.78	3.88	3.91	3.93
Hardness	Vickers 500 gm	GPa (kg/mm^2)	10.5 (1075)	11.5 (1175)	12.7 (1300)	12.7 (1300)	14.3 (1459)	15 (1530)	19.6 (2000)
Hardness	–	R45N	78	79	81	81	82	86	90
Fracture toughness	Notched beam	MPa $m^{1/2}$	2–5	3–4	4–5	4–5	4–5	3–4	5–6
Flexural strength (MOR) (3 Point) @ RT	F417-87	MPa (psi × 10^3)	241 (35)	310 (45)	358 (52)	393 (57)	338 (49)	379 (55)	455 (66)
Tensile strength @ RT	–	MPa (psi × 10^3)	117 (17)	151 (22)	200 (29)	221 (32)	172 (25)	200 (29)	275 (40)
Compressive strength @ RT	–	MPa (psi × 10^3)	1378 (200)	1827 (265)	2068 (300)	2241 (325)	2137 (310)	2240 (325)	2413 (350)
Elastic modulus	C848	GPa (psi × 10^6)	172 (25)	303 (44)	310 (45)	345 (50)	379 (55)	379 (55)	393 (57)
Poisson's Ratio	C848	–	0.22	0.22	0.22	0.23	0.23	0.23	0.23
Thermal									
C.T.E. 25–100° C	C 372-96	× 10^{-6}/C	5.5	6.1	6	6.2	6.3	6.5	6.5
C.T.E. 25–300° C	C 372-96	× 10^{-6}/C	5.8	7	6.8	6.8	6.9	7.9	7.9
C.T.E. 25–600° C	C 372-96	× 10^{-6}/C	6.3	7.7	7.5	7.6	7.6	8.1	8.2
Thermal conductivity @ RT	C 408	W/M K	4	19	23	29	30	30	35
Max use temp	–	Celsius (°C)	1540	1650	1700	1700	1675	1675	1700
Electrical									
Dielectric strength (.125" thick)	D 149-97A	V/Mil	225	250	250	260	270	290	422

Property	ASTM Method	Units	AL74 74%	AL95 95%	AL96 96%	AL98 98%	AL995 99.5%	AL9980 99.8%	AL9996 99.96%
Dielectric constant @ 1 MHz	D 150-98	–	7	9	9.1	9.5	9.8	9.8	9.9
Dielectric constant	D 2520-95	–	–	9.2	9.1	9.4	9.7	10	–
@ Gigahertz	D 2520-95	–	–	11	10.9	9.8	9.8	9.6	–
Dielectric loss @ 1 MHz	D 150-98	–	0.0012	0.0006	0.0004	0.0006	0.0002	<.0001	< .0001
Dielectric loss	D 2520-95	–	–	0.0009	0.0007	0.0005	< .0001	< .0001	–
@ gigahertz	D 2520-95	–	–	12.5	10.9	9.8	9.8	9.6	–
Volume resistivity, 25°C	D 257	ohms-cm	$< 1 \times 10^{13}$	$> 1 \times 10^{14}$	$> 1 \times 10^{14}$	$> 1 \times 10^{14}$	$> 1 \times 10^{14}$	$> 1 \times 10^{14}$	$> 1 \times 10^{14}$
Volume resistivity, 300°C	D 1829	ohms-cm	4×10^{10}	5×10^{12}	3×10^{12}	8×10^{11}	1×10^{12}	3×10^{12}	1×10^{13}
Volume resistivity, 500°C	D 1829	ohms-cm	3×10^{7}	3×10^{9}	7×10^{9}	2×10^{9}	5×10^{10}	6×10^{10}	5×10^{12}
Volume resistivity, 700°C	D 1829	ohms-cm	2×10^{6}	3×10^{8}	4×10^{8}	2×10^{8}	2×10^{9}	6×10^{9}	1×10^{12}

Source: Superior Technical Ceramics Corp.

Zirconia

Zirconia ceramics are also called zirconium oxide (ZrO_2). They are derived from a naturally occurring mineral baddeleyite with composition as zirconium dioxide. Zirconia can also be obtained by chemically treating zircon. The manufacturing process options for zirconia include thermal dissociation, fusion decomposition of zircon sand and chlorination of zircon. Zirconia can be processed with injection molding, precision grinding and laser cutting. Injection molding is preferred for bulk production of zirconia components.

These ceramics are characterized by the highest fractural toughness and flexural strength at room temperature when compared with all other aerospace ceramics. Other key properties of zirconia are high coefficient of thermal expansion, low thermal conductivity and high corrosion resistance. These characteristics made zirconia a preferred choice for TBC material.

In most of its applications, zirconia is used in its partially stabilized form. This is because, at high temperatures, zirconia has a tendency to undergo significant volume changes resulting from thermal phase transformation. Each phase of zirconia has different melting points. Thus, the change in phase during operation makes the component vulnerable to damage.

Table 6
Zirconia Phase and Melting Point

Zirconia Phase	Melting point
Monoclinic, baddeleyite	20 –1,170°C
Tetragonal	1,170 –2,370°C
Cubic	2,370 –2,700°C

Source: Matmatch

To prevent this damage zirconia is stabilized with additives such as magnesium oxide, yttrium oxide and calcium oxide. Among the stabilizers for doped zirconia ceramics, yttrium oxide stabilized zirconia (Y_2O_3-ZrO_2) is popular in the aerospace industry and referred as YSZ.

The combination in which yttrium oxide constitutes 7% by weight of YSZ is called 7YSZ and it is the widely used in thermal and structural applications of aerospace. 7YSZ plays a crucial role in the thermal barrier coating for aerospace engines. The reason such partially stabilized zirconia has been in practice for many decades now is because it withstands more thermal cycles than the fully stabilized zirconia.

Table 7
Properties of Yttrium Oxide Stabilized Zirconia

Property	ASTM Method	Units	YTZP 2,000 (Yttria Stabilized)	YTZP 4,000 (Yttria Stabilized)
General				
Crystal size (average)	Thin Section	Microns	1	1
Color	–	–	Ivory	Ivory
Gas permeability	–	atm-cc/sec	Gas tight <10^{-10}	Gas tight <10^{-10}
Water absorption	C 20-97	%	0	0
Mechanical				
Density	C 20-97	G/Cc	6.02	6.07
Hardness	Vickers 500 gm	GPa (kg/mm^2)	12.5 (1250)	12.5 (1250)
Hardness	–	R45N	80	80
Fracture toughness	Notched Beam	MPam$^{1/2}$	10	10
Flexural strength (MOR) (3 Point) @ RT	F417-87	MPa (psi × 10^3	951 (138)	1380 (200)
Tensile strength @ RT	–	MPa (psi × 10^3)	550 (80)	690 (100)
Compressive strength @ RT	–	MPa (psi × 10^3)	2485 (360)	2485 (360)
Elastic modulus	C848	GPa (psi × 10^6)	210 (30)	210 (30)
Poisson's ratio	C848	–	0.3	0.3
Thermal				
C.T.E. 25–100° C	C 372-96	× 10^{-6}/C	6.9	6.9
C.T.E. 25–300° C	C 372-96	× 10^{-6}/C	8.1	8.1

Property	ASTM Method	Units	YTZP 2,000 (Yttria Stabilized)	YTZP 4,000 (Yttria Stabilized)
C.T.E. 25–600° C	C 372-96	$\times 10^{-6}$/C	10.5	10.5
Thermal conductivity @ RT	C 408	W/M K	2.2	2.2
Max use temp	–	Celsius (°C)	500	500
Electrical				
Dielectric strength (.125" thick)	D 149-97A	V/mil	240	240
Dielectric constant @ 1 MHz	D 150-98	–	30	30
Dielectric loss @ 1 MHz	D 150-98	–	0.001	0.001
Volume resistivity, 25°C	D 257	ohms-cm	$> 1 \times 10^{13}$	$> 1 \times 10^{13}$
Volume resistivity, 300°C	D 1829	ohms-cm	1×10^{10}	1×10^{10}
Volume resistivity, 500°C	D 1829	ohms-cm	1 × 106	1×10^{6}
Volume resistivity, 700°C	D 1829	ohms-cm	5×10^{3}	5×10^{3}

Source: Superior Technical Ceramics Corp.

Zirconia is also used in combination with other oxide and non-oxide ceramics to obtain a composite with higher performance characteristics compared to individual ceramics. Addition of zirconia in a composite is mostly intended to increase fracture toughness, hardness and strength of final material. One of the key composites of zirconia is Zirconia Toughened Alumina (ZTA). The composition includes zirconia in the range of 10-20% by wt. By changing the quantity of zirconia in ZTA properties such as mechanical strength and wear resistance can be adjusted as per the requirement of application. This makes ZTA a suitable choice for a cost-performance trade-off between alumina and zirconia.

Table 8
Properties of Zirconia Toughened Alumina

Property	Zirconia Toughened Alumina
Chemical formula	$Zr\text{-}Al_2O_3$
Density	4.1-4.38 g/cm^3
Hardness	1,750-2,100 Knoop
Elasticity	45-49 × 106 psi
Flexure strength	100-145 ksi
Poisson's ratio	0.26
Fracture toughness	5-7 MPa $m^{1/2}$
Coefficient of thermal expansion	8.0-8.1 $\times 10^{-6}$ 1/C
Thermal conductivity	20.0-21.0 W/mK
Shock resistance	325°C
Maximum working temperature	1,650°C

Source: Stanford Advanced Materials

Non-oxides

Non-oxide ceramics are used applications where oxide ceramics are not compatible with the operating environment or not able to meet expectations. Most popular among these non-oxide ceramics are carbides, nitrides and borides. The manufacturing process of non-oxide ceramics involves three steps: preparation of starting powders, mixing these powders, and forming and sintering these compounds. The covalent bond in these ceramics characterizes them with high temperature resistance, thermal shock resistance, high corrosion resistance, and excellent hardness.

The following table shows the melting point and density of different key non-oxide ceramics currently available in industrial applications.

Table 9
Key Carbide and Nitride Ceramics

Ceramic	Melting Temperature [°C]	Density [g/cm^3]
Carbides		
HfC	3887–3890	12.2
TaC	3875–3880	14.5
ZrC	3530	6.7
TiC	3250	4.7
ThC	2625	10.7
Al4C3	2800	3
B4C	2450–2720	2.5
MoC	2692	8.4
WC	2630–2870	15.6
SiC	2300–2700	3.2 (low temperature β-phase cubic → 2100 °C → high temperature α-phase)
Nitrides		
HfN	3310	14
TaN	3100	14.1
ZrN	2980	7.3
TiN	2950	4
ThN	2630	11.5
AlN	2400	3.1
BN	3000	2.25 (hex.) 3.45 (cub.)
VN	2030	6
Si3N4	1900	3.2 (low temperature α-phase hex. → at 1400–1550 °C → high temperature β-phase hex.)
Borides		
HfB2	3250	NA
ZrB2	3200	6.1
TaB2	3050	11.2
TiB2	2950	4.5

Ceramic	Melting Temperature [°C]	Density [g/cm³]
Silicide		
HfSi	2100	NA
ZrSi2	2100	4.9
TaSi2	2100	NA
MoSi2	2047	6.3

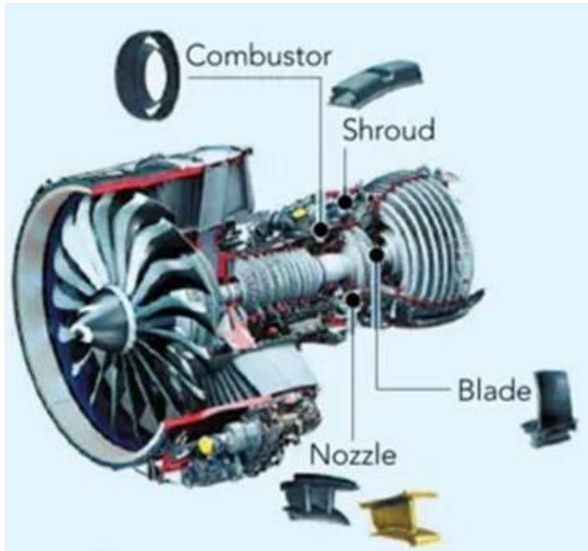
Source: ICT Prague

Silicon Carbide

Silicon carbide (SiC) ceramics are among the most popular ceramics being studied and used in aerospace applications. SiC can be produced using reaction bonding and sintering. The selection of the production process affects the end structure of SiC ceramics. The industrial production process of SiC involves electrochemical reaction between silica (SiO_2) and carbon at high temperature. SiC-based components are manufactured using different processes including hot pressing, sintering, reaction sintering, CVD, and silicon-carbon-fiber-reinforcing.

Key characteristics of SiC ceramics are low dielectric loss, low density, high strength, oxidation resistance, excellent thermal shock resistance, low thermal expansion, and high thermal conductivity. SiC ceramics and composites are used in electronic component manufacturing for aerospace applications. These components help the industry achieve the same performance as silicon-based components at higher operating temperatures. SiC MOSFETs have been observed to provide double power density with much smaller and lighter packaging than the existing MOSFETs. Thus, their popularity and demand are increasing in the aerospace industry.

Figure 2
SiC/SiC Composite Parts in GE9X Engine



Source: GE Aviation

Thermal applications of SiC in the aerospace industry are growing, with a focus on development of engine components subject to high temperatures. These components are estimated to make engine more compact, lightweight and highly fuel efficient. Companies such as GE Aviation and CFM International are key players in the segment. GE Aviation is using SiC CMCs in its GE9X engine, which uses five components made of SiC. CFM International also uses SiC CMC-based shrouds in its engines. These shrouds are made by GE Aviation.

Table 10
Silicon Carbide Ceramic Properties

Properties	Units	Test	Value
General			
Chemical formula			α-SiC
Density, ρ	g/cm^3	ASTM C20	3.21
Color			dark gray
Crystal structure			hexagonal
Water absorption	% at room temperature (R.T.)	ASTM C373	0
Hardness	Mohs		09-Oct
Hardness	Knoop (kg/mm^2)	Knoop 100 g	2800
Mechanical			
Compressive strength	MPa @ R.T.	ASTM C773	1725–2500
Tensile strength	MPa @ R.T.	ACMA Test #4	310

Properties	Units	Test	Value
Modulus of elasticity (Young's modulus)	GPa	ASTM C848	476
Flexural strength (MOR)	MPa @ R.T.	ASTM F417	324
Poisson's ratio, υ		ASTM C818	0.19
Fracture toughness, KIc	MPa × $m^{1/2}$	Notched Beam Test	4
Thermal			
Max. use temperature (in air)	0C	No load cond.	1400
Thermal shock resistance	ΔT (°C)	Quenching	350–500
Thermal conductivity	W/m-K @ R.T.	ASTM C408	41
Coefficient of linear thermal expansion, αl	mm/m-°C (~25°C through ±1000ºC)	ASTM C372	5.12
Specific heat, cp	cal/g-°C @ R.T.	ASTM C351	0.15
Electrical			
Dielectric constant	1 MHz @ R.T.	ASTM D150	10.2
Dielectric strength	kV/mm	ASTM D116	NA
Electrical resistivity	Ωcm @ R.T.	ASTM D1829	1018

NA= Not available in source.

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

Silicon Nitride

Silicon nitride (Si_3N_4) is an upcoming material used in electrical and structural applications in the aerospace industry; it is classified as a non-oxide ceramic. Silicon nitride ceramics have low density, high dielectric strength, creep-resistance, and high thermal shock resistance. This material is widely used in production of structural components such as ball bearings, radomes, RF windows, and engine components such as ignitor insulators. Silicon nitride can be processed using isostatic pressing, die pressing and injection molding to manufacture components.

Table 11
Silicon Nitride Ceramic Properties

Property	ASTM Method	Units	Silicon Nitride (Si3N4)
General			
Crystal size (average)	Thin Section	Microns	4
Color	–	–	Black
Gas permeability	–	atm-cc/sec	Gas tight $<10^{-10}$
Water absorption	C 20-97	%	0
Mechanical			
Density	C 20-97	G/Cc	3.25
Hardness	Vickers 500 gm	GPa (kg/mm^2)	15 (1529)
Hardness	–	R45N	83
Fracture toughness	Notched Beam	MPam1/2	6
Flexural strength (MOR) (3 Point) @ RT	F417-87	MPa (psi × 10^3)	900 (130)

Property	ASTM Method	Units	Silicon Nitride (Si3N4)
Tensile strength @ RT	–	MPa (psi × 10^3)	537 (78)
Compressive strength @ RT	–	MPa (psi × 10^3)	2500 (362)
Elastic modulus	C848	GPa (psi × 10^6)	300 (44)
Poisson's Ratio	C848	–	0.28
Thermal			
C.T.E. 25–600° C	C 372-96	× 10-6/C	2.9
Thermal conductivity @ RT	C 408	W/M K	29
Max use temp	–	Celsius (°C)	1400
Electrical			
Dielectric strength (.125" thick)	D 149-97A	V/mil	300
Dielectric constant @ 1 MHz	D 150-98	–	9.2
Volume resistivity, 25°C	D 257	ohms-cm	> 1 × 10^{14}

Source: Superior Technology Ceramics

Silicon nitride is a result of chemical reaction between silicon and nitrogen, which can be achieved through different production processes such as reaction bonding, hot pressing and sintering. Each process changes the performance properties of silicon nitride, especially density. Thus, the selection of manufacturing process becomes important for the end-application purpose. The different types of silicon nitrides produced with different manufacturing processes are:

- Reaction–bonded silicon nitride (RBSN).
- Hot pressed silicon nitride (HPSN).
- Sintered reaction–bonded silicon nitride (SRBSN).
- Sintered silicon nitride (SSN).

Table 12
Different Silicon Carbide Ceramics and Their Properties

Property	RBSN	HPSN	SRBSN	SSN
3 point RT modulus of rupture (MPa)	200	700	700	850
RT Young's modulus of elasticity (GPa)	175	300	300	300
RT Hardness Vickers Hv0.3 (kg/mm^2)	800	1650	1450	1450
Fracture toughness K^1C (MPam½)	2.5	4.5	6	7.5
Density (g/cc)	2.3	3.2	3.3	3.24
Porosity (%)	30	0	5	0
Thermal expansion coeff. (0-1200°C) (10^{-6}/K-1)	3.2	3.2	3.1	3.1
RT thermal conductivity (W/m/K)	10	26	25	22
Thermal shock resistance (ΔT°C)	400	700	700	800
RT electrical resistivity (ohm m)	1010	1010	1010	1010

Source: International Syalons (Newcastle) Ltd.

Composites

Composites in aerospace applications are comprised of three product categories: fiber-reinforced polymers (FRP), metal matrix composites (MMC) and ceramic matrix composites (CMC). FRPs are characterized by high strength, stiffness and low density; however, they are subject to thermal and chemical degradation at high temperatures. For example, carbon FRP starts undergoing structural degradation at 3,000°C. MMCs and CMCs are suitable for high-temperature operations where FRPs tend to fail.

CMCs are used in components subject to high temperatures such as engine combustor inlets and exhaust nozzles. The components made of woven CMCs enable aircraft engines to operate at high temperatures without the need for cooling systems. Another application is aircraft brakes where the operating temperature can go up to 1,200°C. Carbon fiber-reinforced silicon carbide is preferred in brakes due to its high coefficient of friction, high strength and resistance to oxidation. The CMCs are also used in antennas and other electronic equipment.

The ceramic composites used in the aerospace industry are mostly based on glass and carbon. Materials such as ceramic and glass are brittle by nature. Thus, they are reinforced with other material fibers to gain toughness and strength. The reinforcement materials can be metals or non-metals such oxide and non-oxide ceramics.

Table 13
Comparison between Metals and Composites

Materials	Strength	Drawback
Metals (aluminum alloys)	• Standardization and reparability Static behavior Improvement potential	• High material density Fatigue- and corrosion-related problems High costs of new alloys
Composites (CFRP)	• Fatigue behavior Low density and no corrosion Best suited for light-weight structures	• Poor Impact behavior No plasticity Reparability and recycling

Source: BCC Research

Glass ceramics are an important part of structural applications in the aerospace industry for components such as sensors, displays, control system interactions, and solid oxide fuel cells. These ceramics find applications in canopies, windows, lenses, lighting, and panels. Glass ceramics with high transparency, high temperature stability, shock resistance, and light weight are always in demand from the aerospace industry.

Another form of glass ceramics used in aerospace industry is reinforcing fibers. Glass can be incorporated with high-performance fibers to attain higher strength and toughness. High-modulus ceramic materials are reinforced with materials with low-modulus materials in the matrix, thereby balancing the structural properties of the final material.

These materials have elastic moduli range from 210 to 710 GPa while that of glass and glass composites range from 60 to 85 GPa. Also, some composites of glass can withstand temperatures as high as 1,200°C. The high elastic modulus and high operating temperature stability helps glass ceramic components maintain structural integrity under high extreme environments.

Figure 3
Applications of Glass Ceramics in Aerospace

Source: Elan Technology

The manufacturing process of glass fiber-reinforced polymer (GFRP) ceramics includes five steps: batching, melting, fiberization, coating, and drying and packaging. GFRP has high strength-to-weight ratio so it plays a key role in structural applications in the aerospace industry. The production cost of this material is much less compared to the competitor materials such as carbon fiber-reinforced materials. The GFRP-based products can be manufactured using methods such as sheet molding compound (SMC)/bulk molding compound (BMC), open mold, resin transfer molding (RTM), continuous processing, pipes and tanks, glass mat-reinforced thermoplastics (GMT)/long fiber-reinforced thermoplastics (LFT).

The following table shows the production of GFRP composites by processes/components in Europe:

Table 14
GFRP Production, by Process/Component in Europe
(Kilotons)

Process/Component	2016	2017	2018	2019	2020 (Estimated)
SMC/BMC	274	280	285	287	244
Open mold	237	238	239	237	209
RTM	141	146	148	148	131
Continuous processing	139	146	151	150	135
Pipes and tanks	148	145	148	146	130
GMT/LFT	140	145	152	156	132
Others	17	18	18	17	15
Total market	1,096	1,118	1,141	1,141	996

Source: AVK - Industrial Association for Reinforced Plastics

Table 15
GFRP Production, by Country in Europe
(Kilotons)

Country	2016	2017	2018	2019	2020 (Estimated)
U.K./Ireland	152	153	155	155	128
Belgium/Netherlands/Luxembourg	45	46	46	45	40
Finland/Norway/Sweden/Denmark	40	40	40	39	34
Spain/Portugal	158	161	167	166	141
Italy	154	158	162	161	135
France	110	112	115	114	96
Germany	220	226	229	225	207
Austria/Switzerland	18	19	19	19	17
Eastern Europe*	199	203	208	217	198
Total market	1,096	1,118	1,141	1,141	996

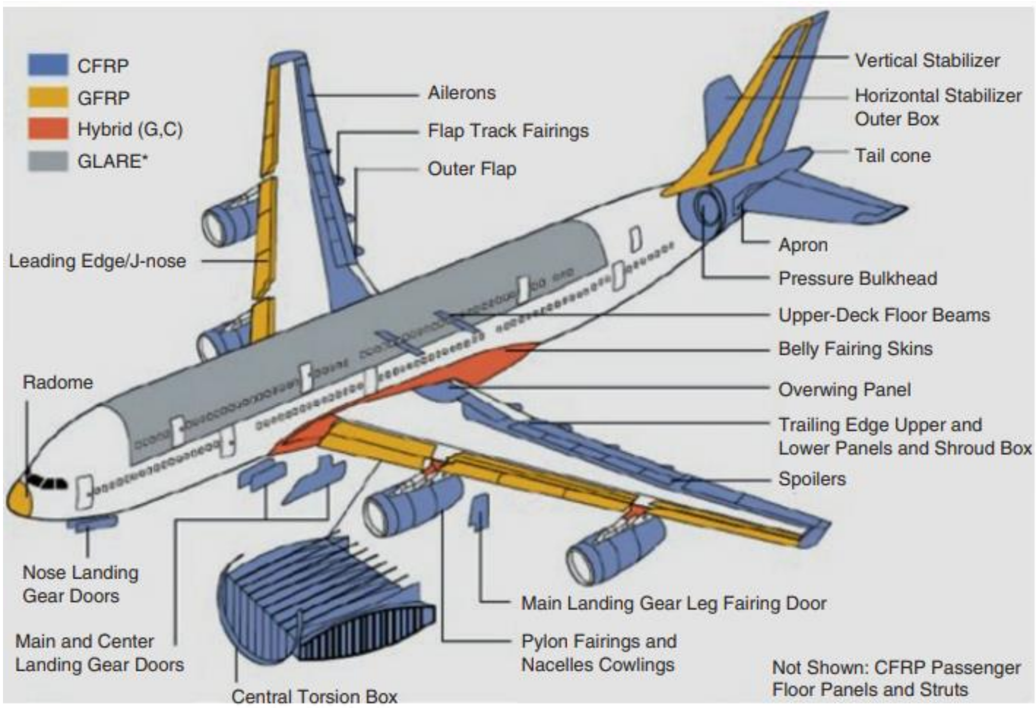
Eastern Europe* = Poland, Czech Republic, Hungary, Romania, Serbia, Croatia, Macedonia, Latvia, Lithuania, Slovakia and Slovenia

Source: AVK - Industrial Association for Reinforced Plastics

Another important composite based on glass is glass-fiber-reinforced aluminum alloy, also known as glass and aluminum-reinforced epoxy (GLARE). This material is characterized by excellent fatigue resistance, high corrosion resistance and less density, making it a better choice as an alternate material compared to aluminum alloys in structural applications. For instance, GLARE components weigh 15% to 30% less than comparable aluminum alloy components.

Airbus uses GLARE in its A380 planes as material for the upper fuselage and the leading edges of the stabilizers. Also, GFRP is being used in A380 floor panels. As well, the glass matrix composites are suitable for high-temperature components such as engine heat shields.

Figure 4
Composites in Airbus A380 Structure



Source: Composite Materials: Applications in Engineering, Biomedicine and Food Science

Table 16
Leading Commercial Aircraft Models and Materials

Manufacturer	Model	Composites by %wt.
Airbus	A300	4.5
	A310	6
	A320	10
	A340	13
	A380	25
	A350	53
Boeing	B747	1
	B757	3
	B767	3
	B777	11
	B787	50

Source: BCC Research

Carbon fiber-reinforced polymer ceramics play a crucial role in today's aircraft structure. CFRP-based products can be manufactured by molding, thereby enabling production of complex components. These components provide better mechanical performance than almost all other materials. The growing share of composites in aircraft is mostly due to increasing use of GFRP and CFRP in structural applications. Composites are used to build complex light-weight structures in drones and airplanes. The lower weight enables airlines to increase their profit margin through fuel efficiency.

Over the last decade, the demand for CFRP has grown 300% due to its growing use in the aerospace industry. As of 2020, the global production capacity of carbon fibers exceeds 150 kilotons per annum and aerospace accounts for the largest share in consumption led by Boeing and Airbus. The Asia-Pacific region has the largest share in the manufacture of CFRP as most manufacturers are headquartered in Asian countries, while the demand in aerospace applications is concentrated in North America and Europe.

The following table lists the top companies with their production facilities for precursor and CFRP in 2014.

Table 17
Leading Manufacturers of CF and Precursor

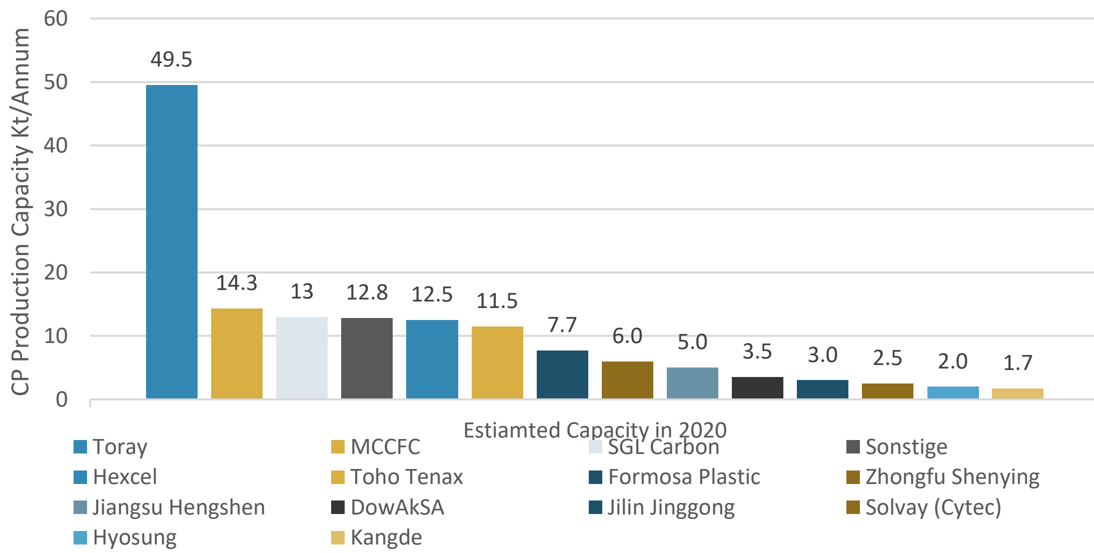
Company	Manufacturing Location	Precursor	Carbon Fiber	Aerospace Applications
Toray (+ Zoltek)	Ehime, Japan	Yes	Yes	Boeing 787, Airbus
	Decatur, AL, U.S.	Yes	Yes	
	Abidos, France	Yes	Yes	
	Gumi, South Korea	–	Yes	
	St. Charles, MO, U.S.	–	Yes	
	Abilene, TX, U.S.	–	Yes	
	El Salto, Mexico	Yes	Yes	
	Nyergesujfalu, Hungary	Yes	Yes	
Toho Tenax	Mishima, Japan	Yes	Yes	Bombardier CSeries, Airbus A380
	Oberbruch, Germany	–	Yes	
	Rockwood, TN, U.S.	–	Yes	
MCCFC	Toyohashi, Japan	Yes	Yes	Airbus A380
	Otake, Japan	Yes	Yes	
	Sacramento, CA, U.S.	–	Yes	
	Germany	–	Yes	
Formosa Plastics	Mailiao, Japan	Yes	Yes	–
SGL	Muir of Ord, U.K.	Yes	Yes	–
	Moses Lake, WA, U.S.	–	Yes	
	Evanston, WY, U.S.	–	Yes	
	Lavardio, Portugal	Yes	Yes	
	Otake, Japan	Yes	–	
	Germany	–	Yes	
Hexcel	Salt Lake City, UT, U.S.	–	Yes	Airbus A350, A380
	Decatur, AL, U.S.	Yes	–	
	Illescas, Spain	–	Yes	
Cytec	Greenville, SC, U.S.	Yes	Yes	Bombardier, F-35, COMAC C919
	Rock Hill, SC, U.S.	Yes	Yes	
Dow/AkSA	Yalova, Turkey	Yes	Yes	–
Hyosung	South Korea	Yes	Yes	–
Kemrock	Vadodara, India	Yes	Yes	–
Alabuga Fibre Ltd.	Balakovo, Russia	Yes	Yes	–

MCCFC= Mitsubishi Chemical Carbon Fiber and Composites

Source: Global Carbon Fiber Composites Supply Chain Competitiveness Analysis, CEMAC

The following figure lists the estimated production CF capacity by company in 2020.

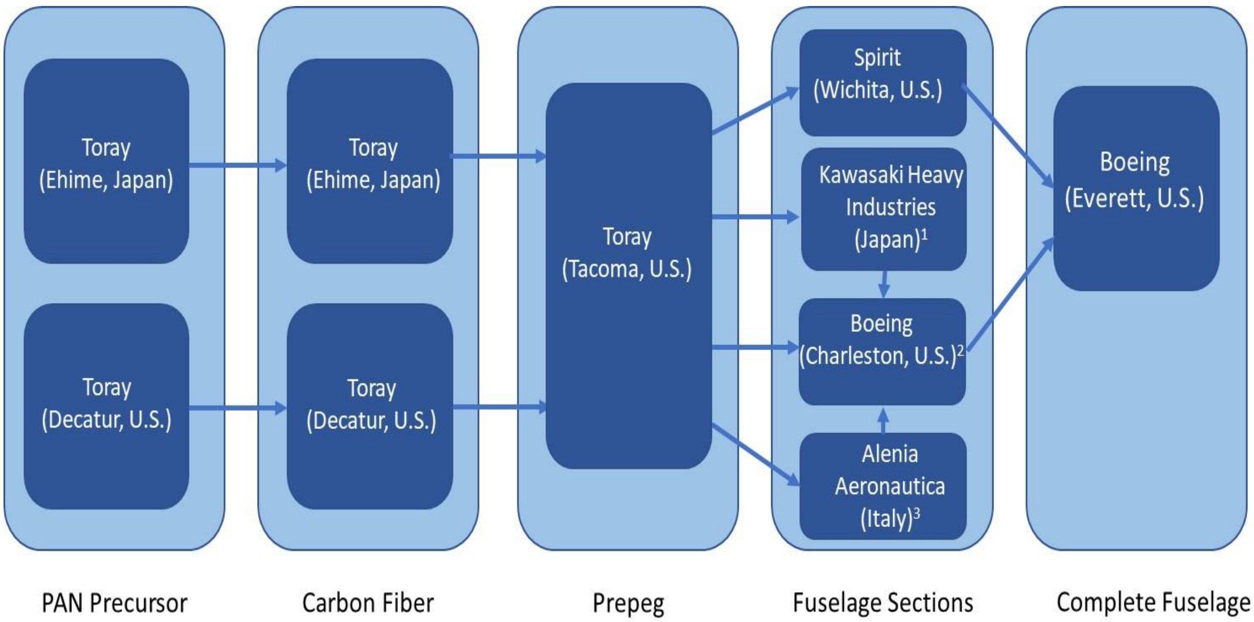
Figure 5
Global Carbon Fiber Production, by Top Manufacturers, 2020
(Kiloton/year)



Source: Composites United E.V.

The following figure shows the carbon fiber supply chain for the Boeing 787 Fuselage.

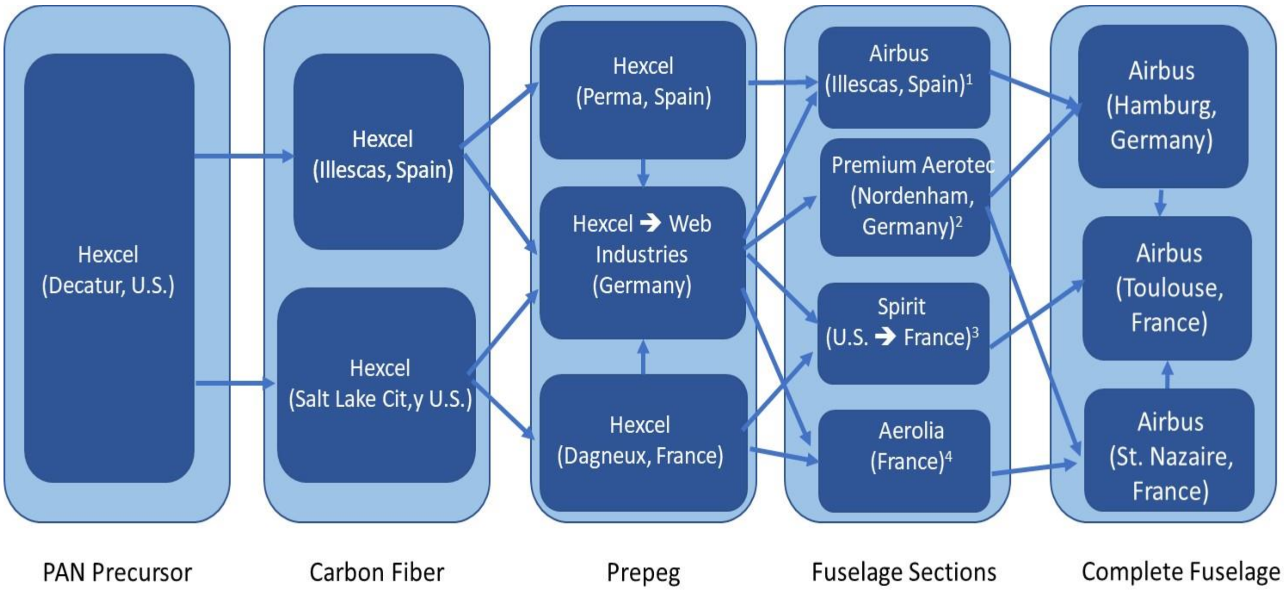
Figure 6
Boeing 787 Fuselage Carbon Fiber Supply Chain



Source: Global Carbon Fiber Composites Supply Chain Competitiveness Analysis, CEMAC

1= 1 Middle Section, 2= Rear Sections and Joins Middle Section, and 3= 2 Middle Sections. PAN= Polyacrylonitrile

Figure 7
Airbus A350 XWB Fuselage Carbon Fiber Supply Chain



Source: Global Carbon Fiber Composites Supply Chain Competitiveness Analysis, CEMAC

1= Rear Barrel, 2= Rear and Fore Sections, 3= Center Section, and 4= Nose.

Table 18
Global Market for Aerospace Composites, by Region, Through 2026
($ Millions)

Region	2020	2021	2026	CAGR% 2021–2026
North America	1,431.4	1,525.9	3,009.9	14.6
Europe	1,180.9	1,214.4	2,312.5	13.7
APAC	715.8	728.6	1,558.4	16.4
RoW	250.5	305.1	431.3	7.2
Total	3,578.6	3,774.0	7,312.1	14.1

Source: BCC Research

Table 19
North American Market for Aerospace Composites, by Country, Through 2026
($ Millions)

Country	2020	2021	2026	CAGR% 2021–2026
U.S.	1,288.3	1,378.5	2,724.7	14.6
Canada	143.1	147.4	285.1	14.1
Total	1,431.4	1,525.9	3,009.9	14.6

Source: BCC Research

Table 20
European Market for Aerospace Composites, by Country, Through 2026
($ Millions)

Country	2020	2021	2026	CAGR% 2021–2026
U.K.	295.2	304.1	567.7	13.3
France	531.4	547.4	1,053.9	14.0
Germany	153.5	158.1	296.5	13.4
Rest of Europe	200.8	204.8	394.3	14.0
Total	1,180.9	1,214.4	2,312.5	13.7

Source: BCC Research

Table 21
Asia-Pacific Market for Aerospace Composites, by Country, Through 2026
($ Millions)

Country	2020	2021	2026	CAGR% 2021–2026
China	286.3	294.9	697.8	18.8
Japan	322.1	325.3	618.1	13.7
South Korea	35.8	36.1	74.3	15.5
Rest of APAC	71.6	72.3	168.2	18.4
Total	715.7	728.6	1,558.4	16.4

Source: BCC Research

Table 22
Rest of the World Market for Aerospace Composites, by Subregion, Through 2026
($ Millions)

Subregion	2020	2021	2026	CAGR% 2021-2026
Middle East and Africa	112.7	115.0	223.3	14.2
South America	137.8	190.1	208.0	1.8
Total	250.5	305.1	431.3	7.2

Source: BCC Research

Chapter 5

Market Breakdown by Application

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Chapter 5: Market Breakdown by Application

In the aerospace industry, material selection for component manufacturing is made on the basis of durability, physical properties and producibility. The materials are expected to withstand vibration and thermal shock during operation while maintaining their physical properties. Also, the tradeoff between cost of production and the advantage of using the materials plays a significant role in material selection. Ceramics and their composites successfully meet the criteria for such applications. These materials also possess properties such as light weight, high energy ablation and high chemicals resistance.

Table 23
Global Market for Aerospace Ceramics, by Application, Through 2026
($ Millions)

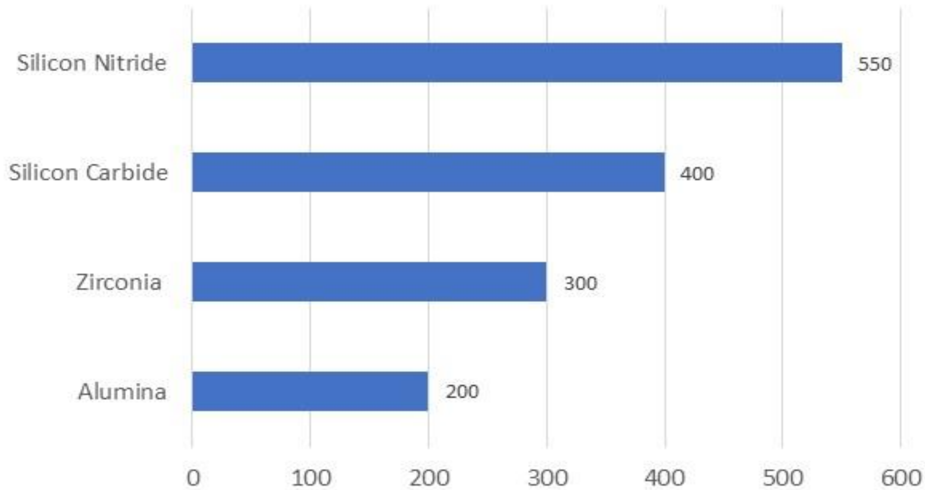
Application	2020	2021	2026	CAGR% 2021-2026
Structural	3,531.5	3,742.0	7,263.5	14.2
Thermal	800.5	824.5	1,077.6	5.5
Electrical	376.7	384.2	467.4	4.0
Total	4,708.7	4,950.7	8,808.5	12.2

Source: BCC Research

Thermal Applications

Thermal applications of a material are decided based on the changes observed in characteristics over a range of temperatures and operation parameters. These parameters can be pressure, chemical reactivity and vibration. The characteristics mainly include coefficient of thermal expansion (CTE), heat conductivity, specific heat, thermal shock resistance, and phase stability.

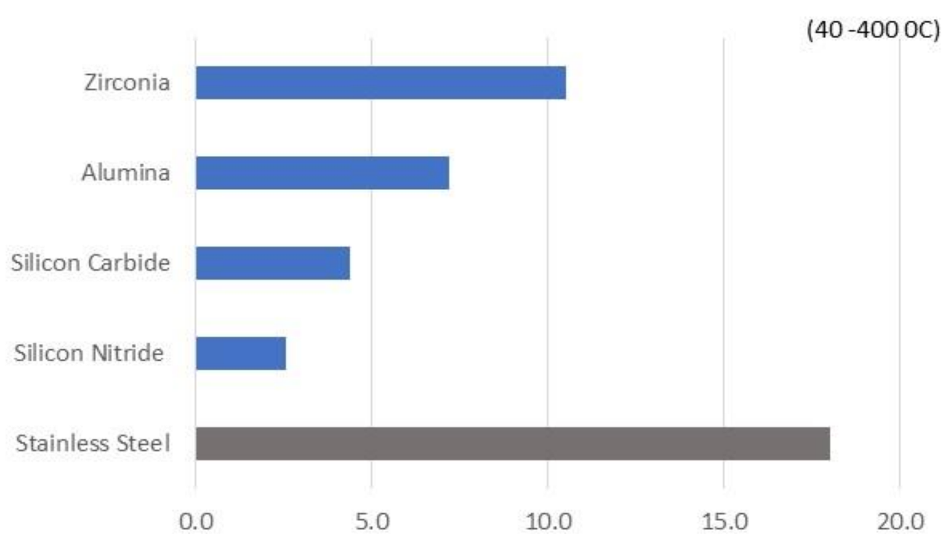
Figure 8
Key Ceramic Materials: Thermal Shock Resistance
(Temperature °C)



Measuring method: JIS R 1648-2002

Source: Kyocera

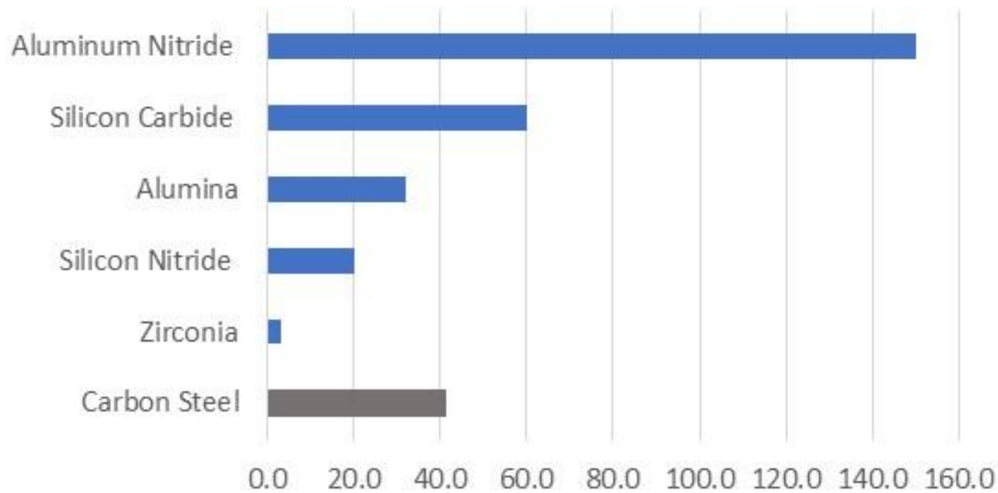
Figure 9
Key Ceramic Materials: Coeff. Of Thermal Expansion
($\times 10^{-6}$/°C)



Measuring method: JIS R 1638-1994

Source: Kyocera

Figure 10
Key Ceramic Materials: Thermal Conductivity at Room Temp.
(W/mK)



Measuring method: JIS R 1611-1997/ISO 18755:2005

Source: Kyocera

The characteristic of specific heat measures the amount of heat required to increase the temperature of a unit mass material by one degree Celsius. This particular property of a material helps in understanding the difficulty of raising the temperature of a material. The higher the specific heat, the more difficult it is to raise the temperature of a material.

Thermal shock means a drastic change in temperature. Such changes cause non-uniform heat distribution, resulting in wear and tear due to irregular heat expansion and contraction in the material. Thus, a material with high thermal shock resistance becomes crucial in maintaining structural stability of a component.

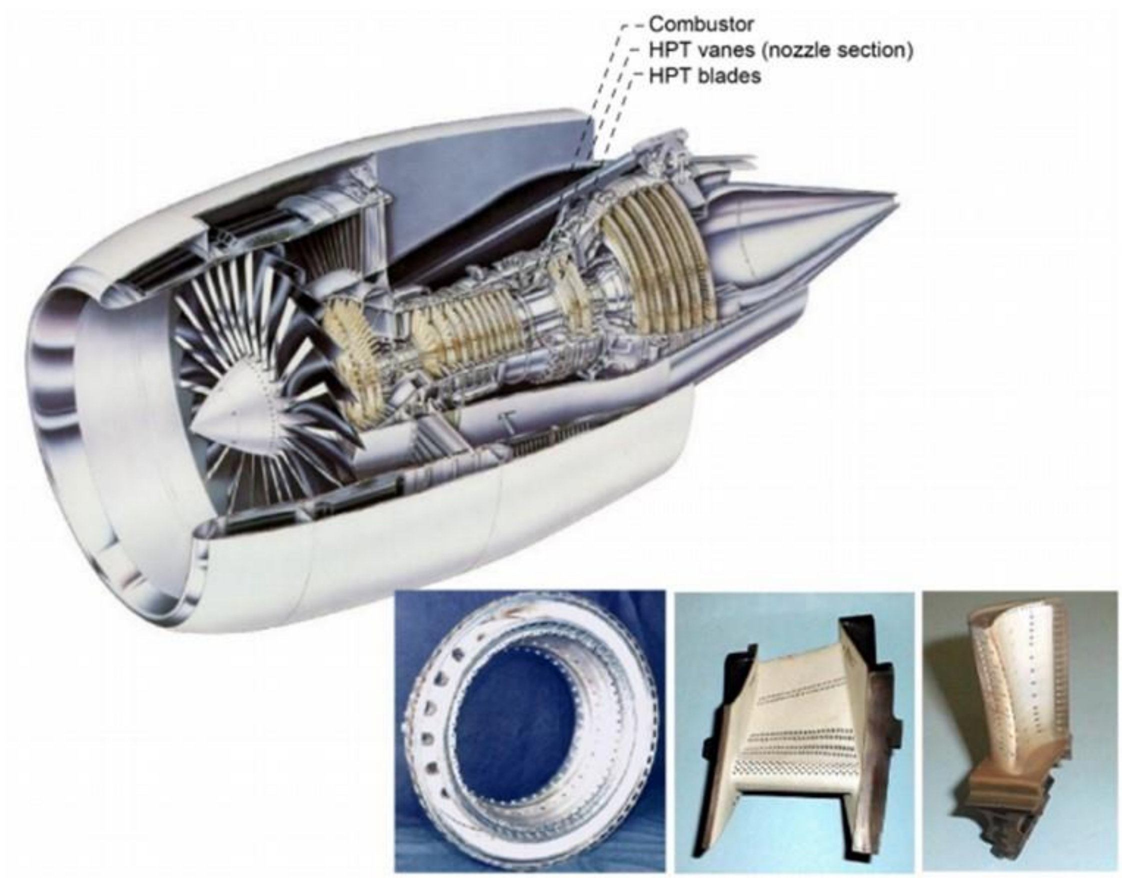
Phase stability is the degree to which a material undergoes physical changes as a response to pressure and temperature changes. Many materials with initially high thermal stability tend to perform otherwise under high pressure environment. In aerospace applications, such change in properties could be disastrous.

Ceramics, compared to most metals, provide a very good combination of the above-mentioned characteristics. They have very low CTE, high specific heat and low thermal conductivity. The main reason for such characteristics is the strong interatomic bonds in ceramic materials. These materials have ionic-covalent bonding with no free electrons to transfer heat or electricity through the material. Thus, ceramics tend to provide excellent thermal insulation even in a high-pressure environment.

Thermal applications of ceramics in aerospace primarily refers to thermal barrier coatings (TBCs) in engine and exhaust systems in aerospace vehicles. Other applications include thermal protection systems for structures for exhaust cones, insulating tiles for the space shuttle and missile nose cones.

In aerospace engines, TBCs help the engine operate at higher temperatures and decrease the need for additional cooling systems. Thus, they increase fuel efficiency and generate overall cost benefits for end-users as well as reduce emissions. The most popular material used in TBCs is yttria-stabilized zirconia (YSZ). This is formulated by stabilizing zirconia (ZrO_2) with yttrium oxide (Y_2O_3).

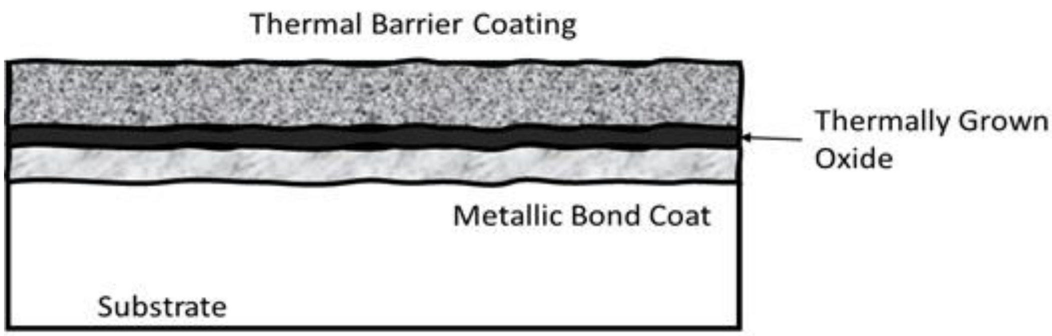
Figure 11
Composite Parts in Jet Engine



Source: NASA/TM—2018-219884

A general TBC consists of two layers, a zirconia coat and a metallic bond coat. Some of the popularly used metallic bond coat composition are NiCrAlY, NoCoCrAlY, CoNiCrAlY, and PtAl. This coat is applied between the metal substate of the component and the ceramic coat to hold them both together. In addition, the bond coat protects the substrate from oxidation during operation.

Figure 12
Thermal Barrier Coating Structure



Source: BCC Research

A third coat named the thermally grown oxide coat (TGO) forms between the bond coat and TBC as a result of artificial or operational oxidation. The artificially or intentionally grown TGO (Al_2O_3) on the bond coat acts as an adhesive medium for the TBC. The TGO can be produced with increasing operational temperature and results in uneven thickness across the surface. This causes coating failure at the interface between other coats.

Among the ceramics and composites, silicon carbide (SiC/SiC composites) is a popular choice for engine component manufacturing. These materials are estimated to need 20% less cooling air thus increasing the efficiency of engines. GE Aviation has invested large amounts in development of SiC-based CMC materials for thermal and structural applications in the aerospace industry. New GE engines are designed with an increased share of SiC composites in the composition of structures. SiC composites when compared to nickel-based alloys provide low density, higher temperature capability, and resistance to oxidation and corrosion.

Another thermal application of ceramics in aerospace are thermal protection systems (TPS) for spacecraft and hypersonic aircraft. TPS protects from high and low temperatures in the operating environments of aerospace vehicles. A space vehicle surface must deal with very high temperatures while travelling through the atmosphere but faces very low temperatures when in space.

TPS act as heat shield for aircraft and protect the vehicles. TPS used in reusable launch vehicles is expected to maintain inner temperature of around 200°C while facing high external temperatures ranging from 600°C to 1,650°C.

Figure 13
Composite in Spacecraft

Source: BCC Research

Ceramics have high energy of ablation, which makes them durable and reusable under the high-temperature environment faced by space vehicles during reentry. For example, with ablation properties, the ceramic layer on the external surface of a space shuttle melts away or shades off after reaching a specific temperature. This prevents transfer of heat from one layer to another, thus keeping the inner side cooler as compared to the external surface.

The materials used in TPS generally include fibers of various types of ceramics such as silica, alumina, zirconia, and alumina-borosilicate (ABS) and advanced material such as CMCs (mostly carbon-based) and phenolic resin-impregnated graphite fibers. Reinforced carbon-carbon composite (RCC) is one of the trending materials in aerospace TPS materials. It acts as a radiator to transmit heat from hot surfaces to cool areas of the structure. This helps to mitigate heat stress across the structure.

Electrical Applications

Some of the key characteristics taken into consideration while selecting material for electrical applications in the aerospace industry are volume resistivity, dielectric strength, dielectric loss, and dielectric constant.

Volume resistivity represents the degree to which a material resists the flow of electrons within itself when a specific voltage is applied across the material. For most materials, volume resistivity changes under high pressure and high temperature conditions. Ceramics tend to sustain their volume resistivity even under harsh conditions. Thus, their demand is consistently increasing for electrical applications in the aerospace industry.

Ceramics have high dielectric strength, which means they can maintain electric resistance over a wide range of voltages. Dielectric loss refers to the dissipation of dielectric energy by materials, which generally takes the form of heat. This heat can interfere with the performance of parts that surround an electric device. Ceramics generate a very low dielectric loss during their operational life, thus are a suitable choice for electric applications.

Ceramics are characterized by inherent high electrical insulation along with piezoelectric and dielectric functions. A typical aircraft has a high number of electronic components such as antennas, capacitors, resistors, and sensors. These products are susceptible to electronic interface during their operation. Ceramics used in these products support them in maintaining normal operations by prohibiting electrical interface.

The piezoelectric applications include ceramic materials to generate electricity directly proportional to the pressure experienced. Also, this function is reversible, which means when a voltage is applied to the material, it undergoes dimensional changes. This function makes piezoelectric ceramics suitable for multiple applications in aerospace industry such as fuel tank sensors.

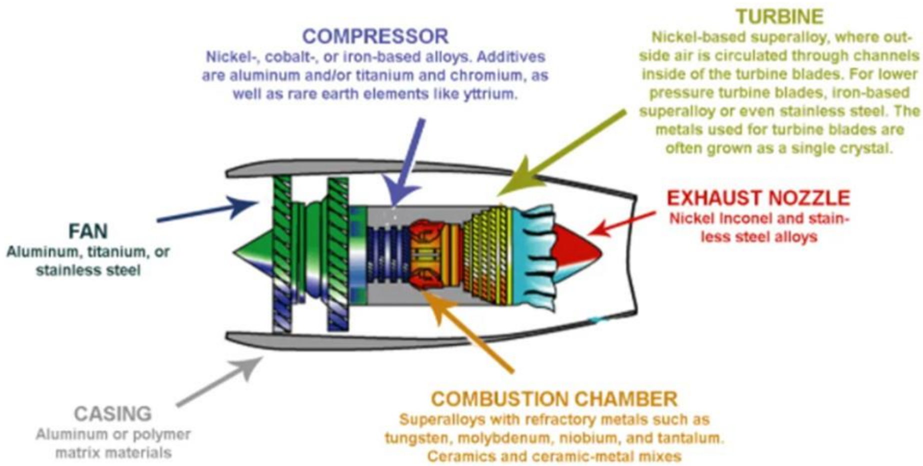
In electrical applications there are other materials such as rubber, polymers and glass that can be considered as alternatives to ceramics. However, ceramics outperform these materials in terms of chemical and thermal resistance, making them a suitable choice for aerospace applications.

Structural Applications

The materials for structural applications in the aerospace industry are selected by considering mechanical properties such as hardness, elastic modulus, density, and compressive strength. All these properties refer to the response of a material to stress and strain experienced during operation, except density. The ability to maintain physical dimensions and structural integrity under extreme environment plays a crucial role for components in aerospace structures.

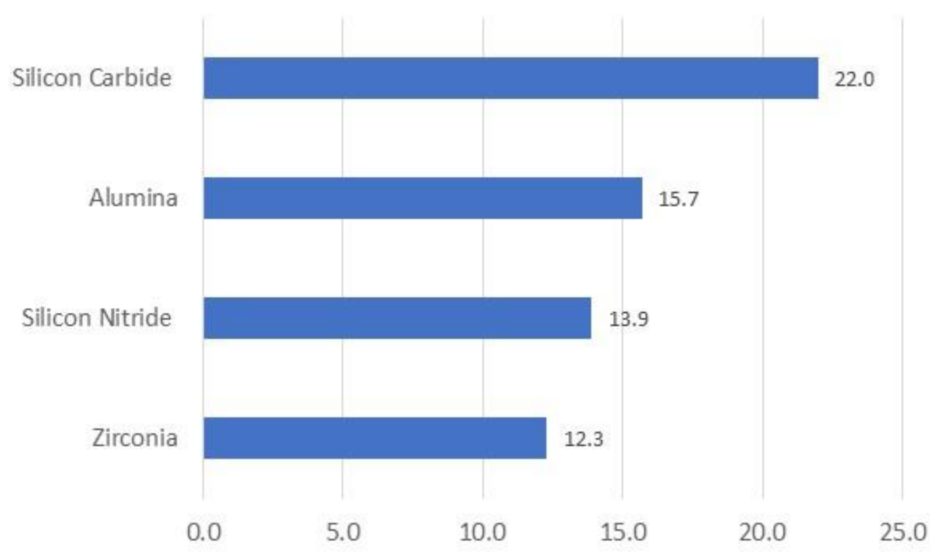
Hardness is the property of resisting structural damage as a response to indentation or abrasion. Elastic modulus is similar to hardness but refers to temporary deformity under stress and strain. High elastic modulus means the material has high resistance to dimensional changes when stress is applied. Compressive strength is the property of a material to withstand forces applied to reduce its size. Density is mass per unit of volume, thus making it inversely proportional to weight. Lower density of a material enables the fabrication of products with less weight than those made from high-density materials.

Figure 14
Generic Diagram of Components and Materials in Jet Engines



Source: Prescouter

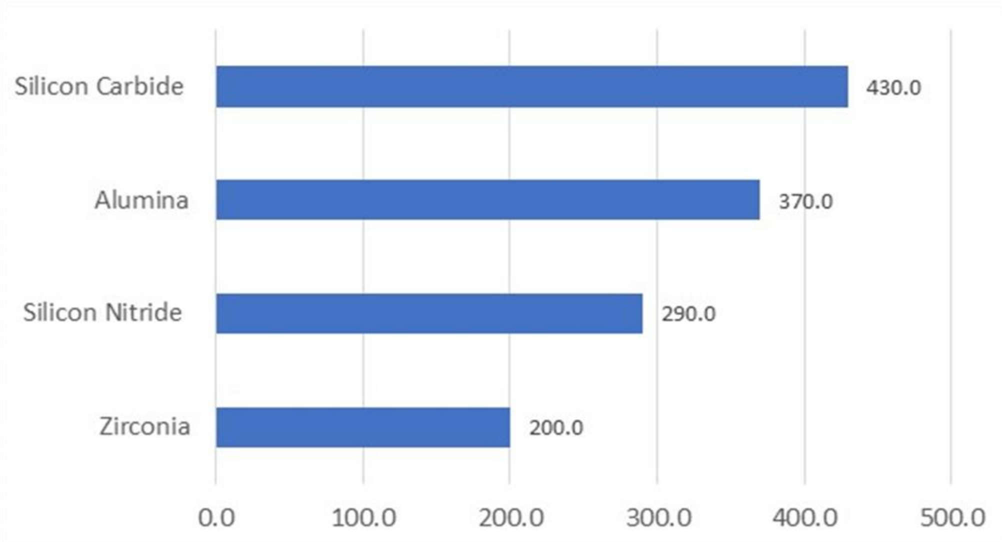
Figure 15
Key Ceramic Materials: Vickers Hardness
(GPa)



Measuring method: JIS R 1607-1990

Source: Kyocera

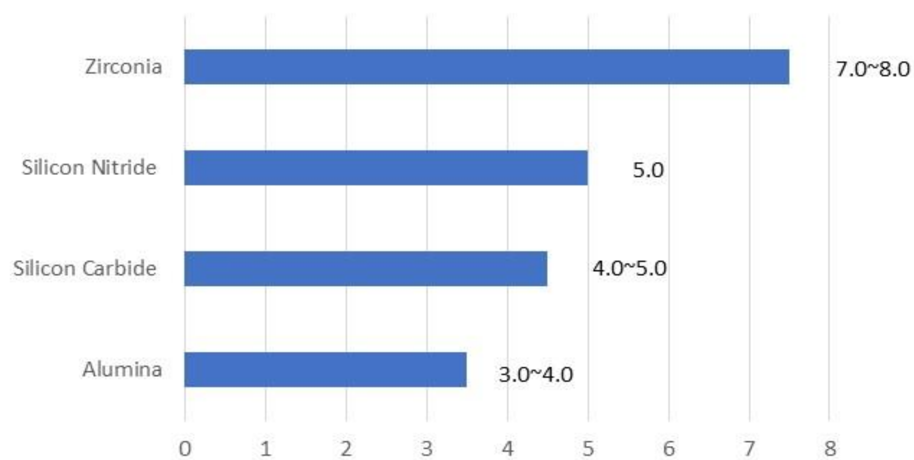
Figure 16
Key Ceramic Materials: Young's Modulus
(GPa)



Measuring method: JIS R 1602-1995

Source: Kyocera

Figure 17
Key Ceramic Materials: Fracture Toughness
(MPa.$m^{0.5}$)



Measuring method: JIS R 1602-1995

Source: Kyocera

Ceramics and ceramic composites inherently possess high hardness, low density, high elastic modulus, and excellent compressive strength compared to most available metals. These materials are rapidly replacing metals in aerospace in high strength and hot environment applications including engine components, brakes and combustor liners. Due to their ability to withstand high temperatures, CMCs are being studied as a replacement for metals as engine component materials.

The following table compares currently used metal alloys and ceramic composites in aerospace

Table 24
Aerospace Material Comparison

Materials	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Density (g/cm^3)
Alloys			
2024 T3	448	73.1	2.78
7075	572	71.7	2.81
6063	241	68.9	2.7
8024	340	77	2.54
AZ31C-F	260	45	1.77
AZ61A-F	310	45	1.8
Ti-6Al-4V Grade 5	950	114	4.43
Ti-5Al-2.5Sn Grade 6	861	110	4.48
INCONEL ×-750	1,250	214	8.28
NIMONIC 80A	1,250	222	8.19
Composites			
Carbon fiber reinforced epoxy resin (unidirectional)	1,550	137.8	1.55
Glass fiber reinforced epoxy resin (unidirectional)	965	39.3	1.85

Source: ICARUS Supermat

Ceramic matrix composites, zirconia and silicon carbide provide excellent structural stability under intense engine heat and high operating pressure. These materials also reduce the weight of components approximately by 50%. This reduced weight directly influences the fuel efficiency of aerospace vehicles. Over the years, the share of composites in the total materials used in an aircraft has increased drastically. The ease of manufacturing smaller and complex components by molding composites provides a competitive edge over their metal alternatives in production of UAVs. Also, airline industry leaders Boeing and Airbus have been investing to a great extent in R&D for lightweight materials. Currently these research activities are focused on composites with ceramics being an integral part of the composition.

Environmental Barrier Coatings

SiC and SiC-based composites are considered the top competitors among the ceramic materials that are replacing metals in the aerospace industry. These materials are known for their excellent oxidation resistance, low density and high strength. However, when silicon comes in contact with water vapor during operation, its reaction results in gaseous silicon hydroxide ($Si(OH)_4$). This causes loss of SiO_2 protective silica and a drop in mechanical strength of the component.

Following is the chemical reaction equation of the process:

$$SiO_2 + 2\ H_2O\ (gas) = Si(OH)_4\ (gas)$$

To prevent such phenomenon, manufacturers have added a new coating called the environmental barrier coating (EBC). These coatings are made up of a mullite-based bond coat or a rare earth disilicate-based bond coat comprising at least three and two layers. Mullite and rare earth disilicates generally have high melting points (~1,800°C). The rare earth silicates used are primarily erbium, yttrium, ytterbium, and lutetium. These coatings are expected to protect SiC materials from recession and degradation while they lack thermochemical resistance to corrosion. This makes it difficult to achieve the result in jet engine applications.

NASA has been developing advanced EBCs to increase the efficiency of SiC-based components. The advanced EBCs used by NASA include HfO2- and ZrO_2-RE_2O_3-SiO_2 EBC systems with HfO_2-Si and rare earth-silicon bond coat systems. These combinations have allowed NASA to achieve heat stability, creep strength, high toughness, and increased erosion resistance. The growing demand for CMCs in aerospace applications will increase the need for EBCs as well, thereby driving the market for ceramics used in EBC production.

Chapter 6

Market Breakdown by Segment

Chapter 6: Market Breakdown by Segment

In this report the aerospace industry is broken down into three segments: commercial, defense and space. The commercial segment refers to aircraft manufactured to cater to demand from airlines, along with business jets, private jets and cargo planes. The defense segment includes aircraft such as fighter jets, unmanned air vehicles (UAV) and drones. Unmanned air vehicles are aircraft that are programmed to operate/fly by themselves while drones are operated manually from remote distances. Spacecraft are designed to be capable of transporting people as well as materials to space.

The commercial aerospace segment accounts for the largest share of the market due to the use of composites to replace metals and alloys in airline vehicles. In the defense segment, though fighter jets are increasingly using composites, the prime driver is exponentially-growing demand from UAVs and drones. Apart from defense, drones are also becoming very popular in other industries as well, such as building and construction, agriculture, and photography.

Table 25
Global Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	2,871.5	2,994.2	3,872.8	5.3
Defense	1,472.4	1,571.7	2,968.9	13.6
Space	364.8	384.8	1,966.8	38.6
Total	4,708.7	4,950.7	8,808.5	12.2

Source: BCC Research

Table 26
Popular Aircraft with Composite Materials Components

Category	Aircrafts
Defense	AV-8B, F-16, F-14, F-18, YF23, F-22, JSF, UCAV, B-2 (Bomber), Harrier GR7, Gripen JAS39, Mirage 2000, Rafael, Eurofighter, Lavi, EADS Mako
Cargo, Passenger	KC135, C17, 777, 767, MD11, A320, A340, A380, Tu204, ATR42, Falcon 900, A300-600
General Aviation	Piaggio, Starship, Premier 1, Cirrus SR 20 and SR 22
Rotary Aircraft	V22, Eurocopter, Comanche, RAH66, BA609, EH101, Super Lynx 300, S92

Source: Aviation Pros

The following table provides information on the composite components found in some key aerospace vehicles.

Table 27
Aircrafts Composite Components and Composites

Category	Aerospace Vehicle	Components	Composites
Sailplanes	SB-10, SB-11, SB-12, Ventus, Nimbus,	Middle portion of the wing	CFRP
	AS-W22	All composite	CFRP
Aero planes	F-14	Stabilator	BFRP
	F-15, F-16 *	Horizontal and vertical tail skins, speed brakes	BFRP, CFRP
	A-4	Flap, stabilator	CFRP
	F-5	Leading edge	CFRP
	Vulcan	Airbrakes	CFRP
	Mirage 2000	Rudder	Boron/carbon/epoxy
	AV-8B	Wing skin, control surfaces, front fuselage	CFRP
	Rafale	Wing structure	CFRP
	Boeing 757 &767	Control surface, cowlings, under-carriage doors, fairings	CFRP
	A 310-300	Fin box	CFRP
	Lear Fan 2100	All composite	CFRP
	Voyager	All composite	CFRP
	Starship	All composite	CFRP
	Airbus, Concorde, Delta 2000, Falcon 900	Brake discs	Carbon/carbon
	C-5A	Wing box	SiC/aluminum
	F-111	Fuselage segment	Boron/aluminum
Rockets and Space Vehicles	Tactical	Nose cone, Inlet	Quartz/polyimide
	Missiles	Fairing, fins	Carbon/polyimide
	Polaris, Minuteman, Poseidon, Trident	Rocket cases	KFRP, GFRP
	Tomahawk	Shaft for turbofan	Borosic/titanium
	PSLV	Upper stage solid motor case	KFRP
	ARIANE	Dual-launch structures, fairings	CFRP
	INTELSAT	Antennas, antenna support structure, multiplexers, solar array wings	CFRP and KFRP
	Viking	Parabolic antenna reflector boom	CFRP sandwich
	Voyager	Parabolic reflector, sub-reflector support structure, dichroic sub-reflector	CFRP and KFRP
	INSAT, ARABSAT, ITALSAT	Antenna reflectors	CFRP
	Space shuttle	Main frame and rib-truss struts, frame stabilizing braces, nose landing, gear and drag-brace struts	Boron/aluminum

Source: Indian Institute of Technology Kharagpur E-Book

Commercial Aerospace Industry

The commercial aerospace segment can be further classified into three sub-segments: passenger, transport (cargo), and business or private. Among these the passenger aircraft segment is the largest segment, followed by the cargo and business segments. The materials composition for commercial and cargo aircrafts are mostly the same while that of business aircrafts may vary a bit.

Commercial passenger aircraft are purchased as either base efficiency or high efficiency models. To increase profits, companies by default prefer purchasing the high efficiency models. The designs of these aircraft mainly focus on higher fuel efficiency, more load-bearing capacity and lower carbon emissions. Customers/buyers of these aircraft, such as commercial airlines, are expected to follow strict pollution norms which in turn impact the manufacturing process of the aircrafts. The manufacturers of commercial aircraft invest large sums in R&D on better materials to cope with the tightening regulations. The prime focus of these R&D activities is to develop lightweight materials with enough strength and stability so that they can replace existing heavy materials such as metals and alloys. The lighter structure helps to achieve higher fuel efficiency and lower emissions, thereby decreasing the expense of operations and increasing profit margin for operators.

Table 28
Global Market for Aerospace Ceramics in Commercial Aerospace, by Region, Through 2026
($ Millions)

Region	2020	2021	2026	CAGR% 2021–2026
North America	1,356.1	1,422.0	1,833.1	5.2
Europe	914.7	946.2	1,178.9	4.5
APAC	402.9	422.3	588.3	6.9
RoW	197.8	203.7	272.6	6.0
Total	2,871.5	2,994.2	3,872.8	5.3

Source: BCC Research

Composites, especially carbon- and glass-based, have become a strong competitor to conventional materials used in aerospace in structural applications. GLARE and CRFP are widely used in aircraft bodies while SiC composites are gaining popularity in engine components. Composites are also preferred in nose, tail and landing gear parts.

Commercial aircraft production is dominated by Boeing (U.S.) and Airbus (France). These two companies account for more than 90% of global commercial aircraft fleet. These companies have most of their operations located in their home countries. Thus, the aerospace ceramics market for commercial aerospace industry is concentrated in the U.S. and France.

Other key players in the commercial aerospace industry are Embraer (Brazil), Bombardier (Canada), Commercial Aircraft Corporation of China COMAC (China), and Cessna Aircraft (U.S.). As China recovered sooner than U.S. and European countries from COVID-19 shutdowns, COMAC was able to resume its aircraft production by the end of 2020. Thus, the demand for ceramics and composites for aerospace applications gained momentum in Asia before the developed regions.

The global aircraft industry suffered significant losses due to COVID-19 shutdowns and decreased travel demand during 2020. The demand for commercial aircraft took a hit, dropping by ~40% compared to 2019. Boeing's deliveries dropped by 57% and those of Airbus dropped by 34%. Also, Boeing had to ground its 737 Max fleet due to technical issues in the sensor system. The order cancellations for Boeing and Airbus cascaded to the leading component manufacturers in the industry, impacting the demand for aerospace ceramics and composites in 2020. Though the commercial aircraft industry is showing signs of recovery, the backlog is still large enough to impact the new production orders of aircraft.

Another factor that has an impact on the commercial aircraft industry is the revenue of airline companies. In 2020, the revenue per kilometer (RPK) dropped more than 65%, pulling down the profits of airlines over a steep slope. As per the International Air Transport Association (IATA), the key performance indicators of commercial airline industry are estimated to stay low during 2021.

The following table shows key indicators for airline industry with forecast values of 2021.

Table 29
Key Performance Indicators of the Airline Industry, 2019–2021

Key Indicators	2019	2020	2021
Net post-tax profit ($ billions)	26.4	-126.4	-47.7
Operating margin (% revenue)	5.2%	-28.2%	-9.4%
RPK growth, YoY % change	4.1%	-65.9%	26.0%
RPK, as % of 2019 level	100%	34.1%	43.0%
Passenger numbers (billion)	4.5	1.8	2.4
Passenger yield, YoY % change	-3.7%	-8.7%	-3%
Cargo yield, YoY % change	-8.2%	40%	5%
Fuel price, USD/barrel	77.0	46.4	68.9
Non-fuel unit costs, YoY % change	0.3%	17.5%	-15.0%

RPK= Revenue per kilometer

Source: IATA

It is estimated that international air travel will grow in 2021 is estimated to only 34% of its pre-COVID level. Such slow growth will negatively impact the production activity for the aerospace industry. The aircraft production industry is not expected to reach pre-COVID levels until the middle of the decade due to existing inventory and low orders. Many industry experts believe that the industry will not recover to a pre-COVID level of orders (2019) until sometime during the period of 2023 to 2025.

Table 30
Top Aircraft Models in the Commercial Airline Industry and Their Deliveries, 2015–2020
(Units)

Models	2015	2016	2017	2018	2019	2020
A220	0	0	0	135	118	64
A320 Family	1,015	698	1,160	577	796	296
A330	156	97	25	37	104	2
A350	16	51	44	62	113	21
A380	3	2	0	20	0	0
Boeing 737	666	701	865	837	69	130
Boeing 747	6	18	6	18	–	1
Boeing 767	49	26	15	40	26	11
Boeing 777	58	23	60	59	38	13
Boeing 787	99	80	107	136	113	29

Source: Airbus, Boeing

Airbus and Boeing are planning to cope with the situation by ramping up the production of their bestselling models in coming years. Airbus will increase the production rate of its A320 family by the end of the year, while Boeing will focus on 737 Max production after the plane's recertification. Also, in 2020 Airbus stopped production of its A380 model as it was not getting the expected response from the airline industry. Boeing is planning to reduce the production rate of its 787 series from 2021 onwards and push back the production of the 777X to 2023. These delayed production schedule of aircraft models which have a high share of composites will impact demand for ceramics in the industry during the forecast period.

Table 31
Leading Business Jet Manufacturers and Their Sell, 2015–2020
(Units)

Company	2015	2016	2017	2018	2019	2020
Airbus	4	1	0	1	6	5
Boeing Business Jets	11	4	10	6	2	1
Bombardier Business Aircraft	199	162	138	137	142	114
Cirrus Aircraft	0	3	22	63	81	73
Dassault Aviation	55	49	49	41	40	34
Embraer	120	117	109	91	109	86
Gulfstream Aerospace Corp.	154	121	120	121	147	127
Honda Aircraft Co.	2	23	43	37	36	31
Pilatus	0	0	0	18	40	41
Textron Aviation (Cessna Aircraft)	166	178	180	188	206	132
Total	711	658	671	703	809	644

Source: General Aviation Manufacturers Association

The business and private jet segment is led by Bombardier and Textron Aviation. Though the number of jets sold under this segment seem comparable to that of the passenger segment, the size of these aircraft is very small when compared to an airline aircraft. Thus, the material consumption during business or private jet production contributes a small share to the ceramic market. Considering the demand side, this is the least affected segment of the aerospace industry. It is estimated the demand for business jets will catch up to 2019 levels by the end of 2021 and continue to grow as it had been prior to the pandemic. North America is the leading consumer of business and private jets, followed by Europe. These regions also contribute the largest share in the business jet production industry. The demand for business jets is estimated to be grow rapidly during 2021–2023 and then normalize during 2023–2025.

Jet engines are another key focus area of applications for ceramics in the aerospace industry. The leading jet engine manufacturers, GE Aviation, Pratt & Whitney, Rolls Royce, and CFM International, have increased their funding for CMC facilities. These companies have managed to increase the performance of jet engines using ceramic or composite components and coatings in their engines. Noticing the benefits, GE and Pratt & Whitney have established separate facilities to increase production and more R&D in the area. Since composites play a vital role in GE's LEAP and GE9X engines, GE started production of SiC composites in Huntsville, Alabama in 2015. Pratt & Whitney established a 60,000 sq. ft. R&D facility in Carlsbad, California in 2019.

Apart from the jet engine manufacturers, the CMC market has other key players such as CoorsTek, 3M, Applied Thin Films, and Ube Industries. The composites industry has seen some interesting developments focused on the aerospace applications. Nakashima Propeller (Japan) managed to develop a composite material that is 40% to 50% lighter than conventional propeller materials, thereby increasing fuel efficiency by 5% to 6%. Toray Industries, another leading CRFP manufacturer from Japan, introduced a high performing CFRP for aircraft engine components. As ceramics and ceramic composites help jet engine manufacturers increase efficiency of their products while reducing emissions, their popularity is growing. With tightening regulations for the airline industry, the demand is therefore expected to grow rapidly along with continuous investments in R&D for better materials.

Defense Aerospace Industry

The defense aerospace segment is different from other aerospace markets as the customer side is a government authority or organization. As the client has its budget allocated at beginning of a year and deal, the demand remains mostly unaffected by the environmental and micro-economic factors. The long-term contracts tend to dilute the impact of short-term disruptions. However, as COVID-19 affected the players in the value chain of the industry it did manage to slow down production to some extent. At the same time, the increasing tensions between regional powers and constant threat of terrorism are expected to fuel the demand for defense aircrafts in coming years.

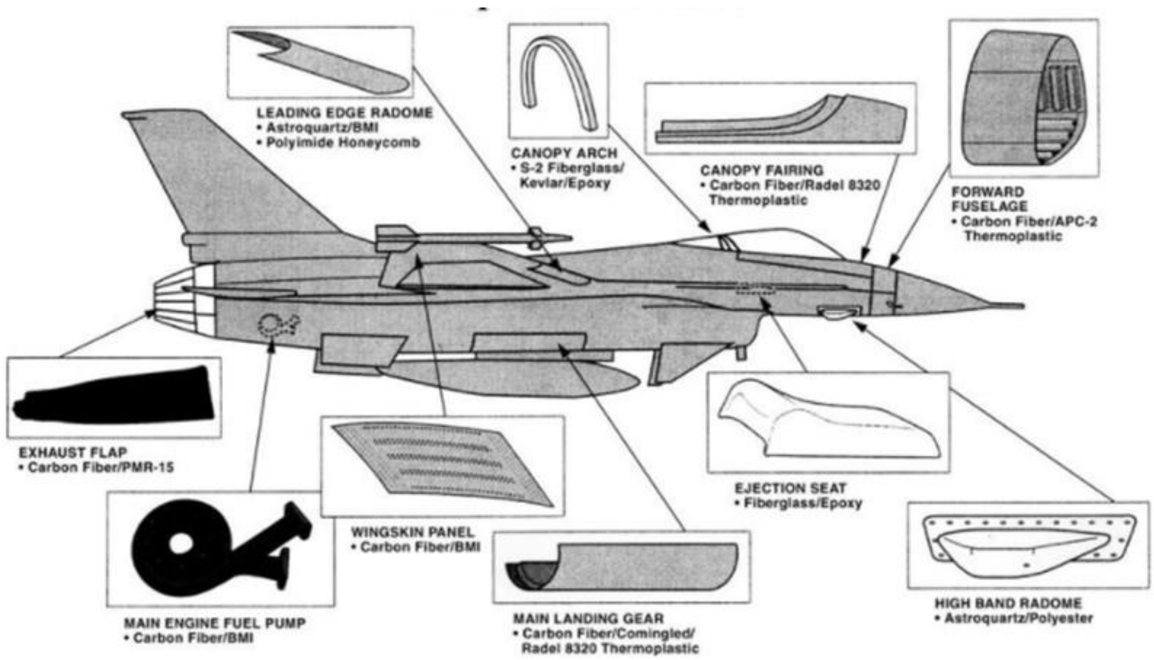
Companies such as Lockheed Martin (U.S.), L3Harris (U.S.) and Rolls Royce (U.K.) registered profit even during the pandemic. Lockheed's revenue growth is due to increased demand for F-35 fighter jets. With decreased prices for the aircraft, the company expects the demand to keep rising during the forecast period.

Table 32
Global Market for Aerospace Ceramics in Defense Aerospace, by Region, Through 2026
($ Millions)

Region	2020	2021	2026	CAGR% 2021–2026
North America	745.9	809.6	1,531.6	13.6
Europe	404.5	424.5	777.5	12.9
APAC	223.1	235.8	480.3	15.3
RoW	98.9	101.8	179.5	12.0
Total	1,472.4	1,571.7	2,968.9	13.6

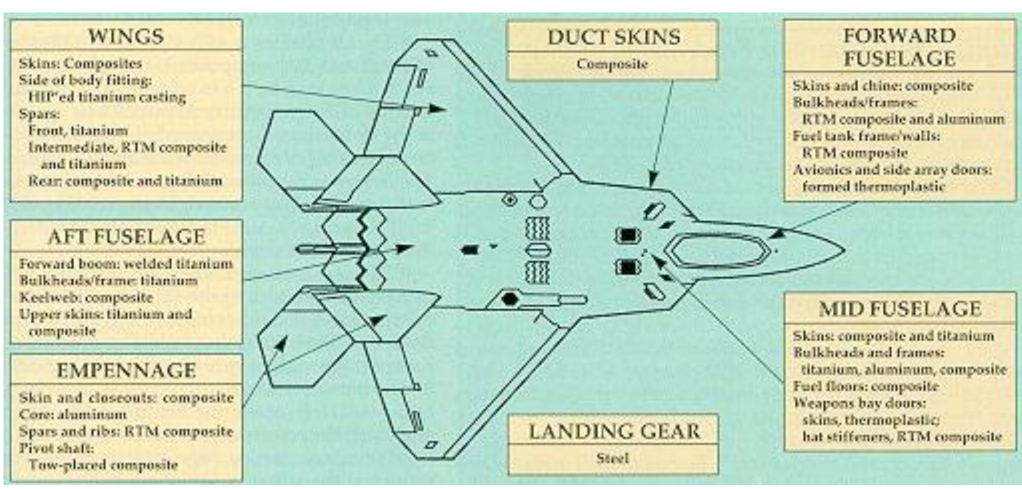
Source: BCC Research

Figure 18
Typical Applications of Composites in Fighter Jets



Source: Composites Horizon

Figure 19
Composition of F-22 Raptor Jet



Source: Aviation Stack Exchange

Figure 20
Composition of Rafale Jet

Source: Dassault Rafale

In 2020, global military expenditures increased by 2.9% on a year-on-year basis, registering the highest total over the past three decades. The percentage share of military expenditure of global GDP increased sharply as there was a COVID-induced drop in global GDP but military expenditures remained constant. The leading countries in the global military market are the U.S., Russia, the U.K., China, and India. According to Stockholm International Peace Research Institute (SIPRI), Africa registered the highest growth in military expenditure followed by Europe and North America during the year. The defense aerospace industry is estimated to follow the military expenditure graph closely, thereby growing in the same pattern. Like the commercial aerospace segment, most of the military aircraft production takes place in North America and Europe. Thus, the growing demand for military aircraft across the globe will subsequently drive the demand for ceramics and composites in North America and Europe during the forecast period.

The following table shows the change in military expenditure over the past two years of the top 10 countries in the world.

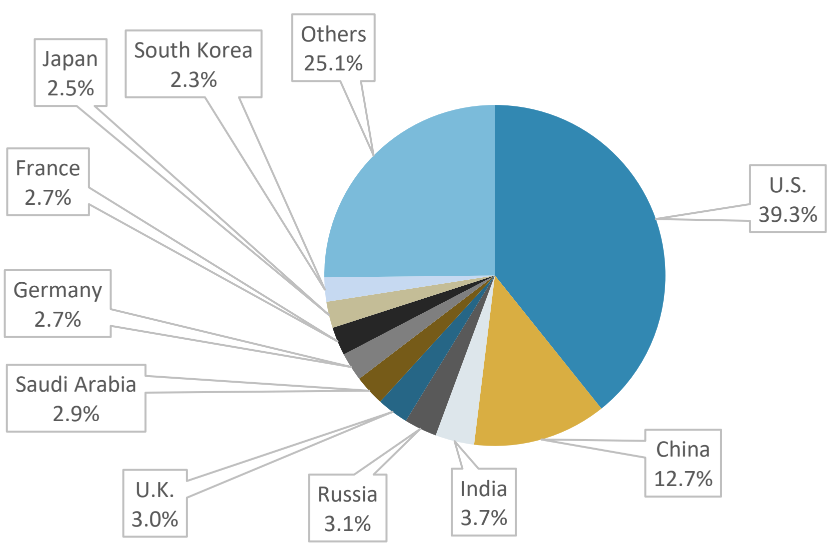
Table 33
Global Military Expenditure, by Top 10 Countries, 2020
($ Billions/%)

Country	Spending, 2020 ($ Bn)	% Change 2019–2020	% Change 2011–2020
U.S.	778.0	4.4	-10.0
China	[252]	1.9	76.0
India	72.9	2.1	34.0
Russia	61.7	2.5	26.0
U.K.	59.2	2.9	-4.2
Saudi Arabia	[57.5]	-10.0	2.3
Germany	52.8	5.2	28.0
France	52.7	2.9	9.8
Japan	49.1	1.2	2.4
South Korea	45.7	4.9	41.0

[] values are estimated by SIPRI.

Source: Stockholm International Peace Research Institute (SIPRI)

Figure 21
Shares of Global Military Expenditure, by Top 10 Countries, 2020
(%)



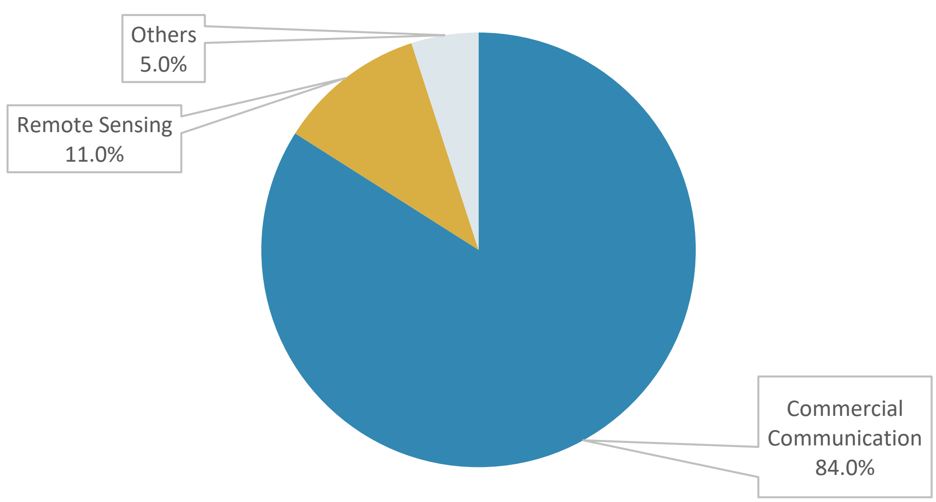
Source: SIPRI

Also, the defense segment includes unmanned air vehicles and drones along with fighter jets and rotorcraft. UAVs and drones are a great help when it comes to surveillance and defense in harsh environment conditions and difficult terrain. Since UAVs and drones often operate in extreme environments the materials they are made of should have high corrosion resistance. Composites can be manufactured using combinations of different materials, thereby giving the UAV or drone specific characteristics. For instance, composites can be designed to absorb certain frequency waves and transmit different frequencies. This can help these craft to avoid being detected on radar and thus avoid anti-air defense systems. These benefits make composites the preferred choice for UAV production. However, the small size of drones leads to less consumption of material when compared to fighter jets and rotorcraft So UAVs and drones contribute a smaller share to the aerospace ceramic market.

Commercial Space Industry

The commercial space industry is expected to be the fastest growing segment during the forecast period. This segment mainly refers to spacecraft and satellites. The rapid growth of the segment is being driven by increasing demand from the small satellites industry. The demand is characterized by applications for imaging and image-based analytics for agriculture, economic forecasting, urban planning, resource management, disaster monitoring, retail, maritime, and other applications. There is also increasing demand for satellite broadcasting in military, telecommunication and entertainment applications. These satellites can be as small as microwaves and cost less than a million dollars. Many countries are investing in infrastructure and technology development to cope with the demand, thereby driving consumption of ceramics and composites in the satellite industry across the globe. The U.S. leads the satellite manufacturing industry; it accounts for more than 60% of the global market.

Figure 22
Shares of Satellites Launched Globally, by End-Use Purpose, 2020
(%)



Others= Military, Scientific, Navigation, and Satellite Servicing

Source: Satellite Industry Association

The space industry needs vehicles similar to the commercial aerospace segment but with more robust performance and higher characteristic ratings. The operating environment of space vehicles is extreme and much different than that of other aerospace segments. The materials used for spacecraft need to be able to sustain performance and shape in the presence of high radiation, friction from the atmosphere and landing impact. The exposure to radiation can trigger surface erosion in materials, which subsequently can result in structural damage. Also, the thermal protection system of a space craft needs to face the high temperatures while passing through atmosphere and the low temperatures while in space. With increasing speed of aircraft and changing designs, spacecraft materials such as ceramics and composites are making their way into aircraft applications to cope with increased performance needs.

Ceramics and composites are widely popular in the spacecraft industry for thermal and structural applications. Composites, especially carbon-based, have been at the center of most of the material developments in the industry. Carbon-based composites are used in the TPS of spacecraft and satellites. Thus, the increasing production rate of spacecraft and satellites will drive the demand for ceramics and composites in the industry.

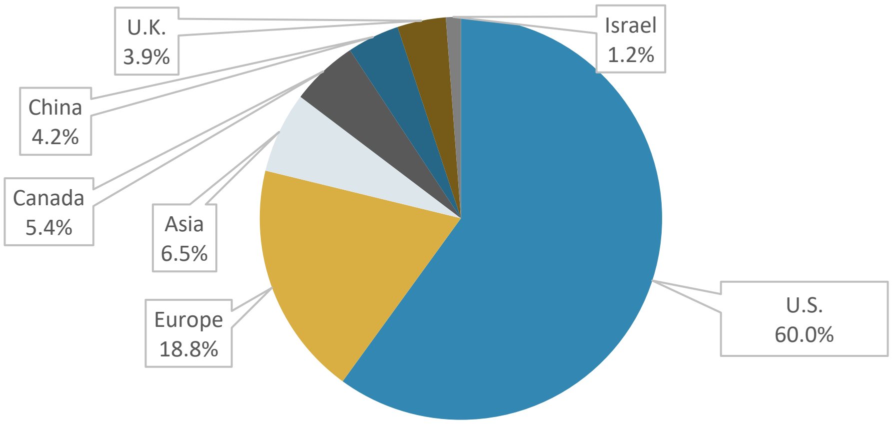
Table 34
Global Market for Aerospace Ceramics in Commercial Space, by Region, Through 2026
($ Millions)

Region	2020	2021	2026	CAGR% 2021–2026
North America	158.2	172.8	902.9	39.2
Europe	93.4	95.6	473.7	37.7
APAC	80.3	82.4	438.0	39.7
RoW	32.9	34.0	152.2	35.0
Total	364.8	384.8	1,966.9	38.6

Source: BCC Research

The space segment is primarily dominated by government agencies from North America and Europe. These regions are also witnessing the rise of private players in the space industry such as Blue Origin, Space X, Boeing, Virgin Galactic, and Lockheed Martin. The U.S. has been at the spearhead of space-related developments for many decades and will to continue in that lead role. The U.S. National Aeronautics and Space Administration (NASA) has led the global space industry in terms of technological developments and funding. However, it is estimated the space industry in the Asia-Pacific region will grow rapidly, with China and India on the frontlines.

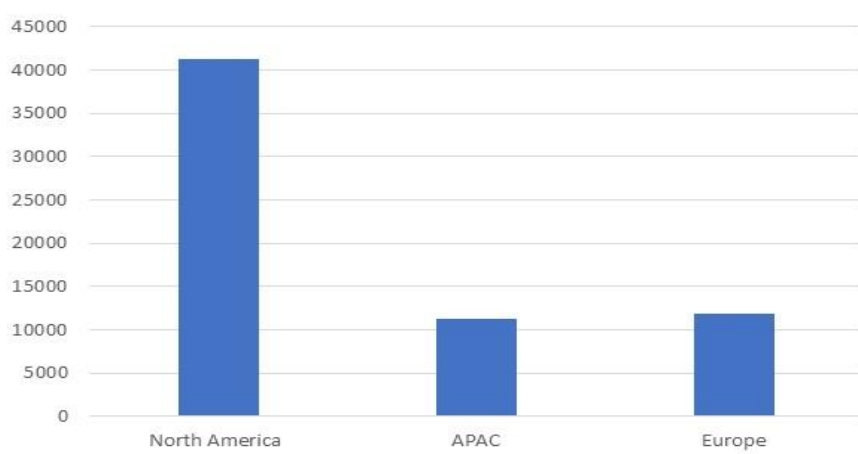
Figure 23
Shares of Global Spacecraft in the Manufacturing Industry, by Geography, 2021
(%)



Source: Space-Tech; the share is calculated based on by number of spacecraft manufacturing-related companies.

As the space segment is still dominated by government agencies, the budget allocation to these agencies plays a crucial role in the growth of the spacecraft and satellite industry. Thus, governmental budget decisions will influence the demand for ceramics and composites in the space applications segment.

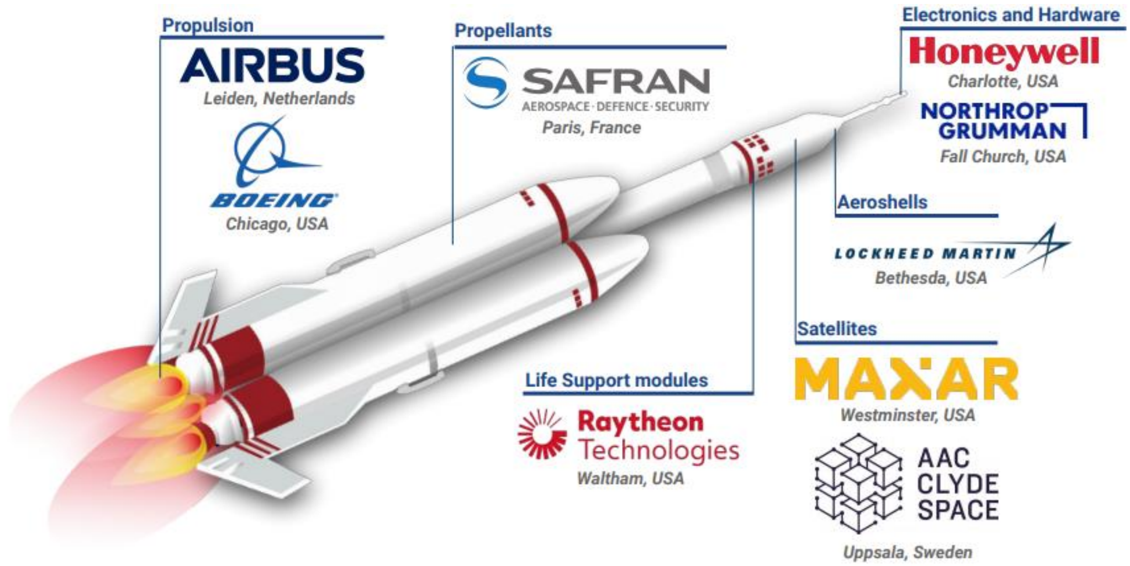
Figure 24
Government Space Budget, by Region, 2021
($ Billions)



Source: Space-Tech

Several private companies have entered the space race which was conventionally considered only to be a national interest. With ambitious leaders, companies such as Blue Origin (U.S.), Boeing (U.S.), Virgin Galactic (U.S.), Space X (U.S.), and Sierra Nevada Corp. (U.S.) are bringing the idea of space tourism into reality. These companies are making large investments in spacecraft construction and development, resulting in the growth of regional markets for spacecraft materials such as ceramics and composites.

Figure 25
Manufacturers of Some Key Rocket Parts



Source: Space-Tech

The following table shows the number of space companies and government agencies which operate in different segments of space industry in the top five countries based on the government budget for the space industry.

Table 35
Companies and Government Agencies in the Space Industry, by Top Five Countries
(Number)

Country	Space Companies	Govt Agencies
U.S.	1,741	22
China	147	3
France	170	2
Russia	8	2
Japan	72	1

Source: Space-Tech

The following table provides a spacecraft and manned spacecraft manufacturers around the globe.

Table 36
Spacecraft Manufacturing Companies Across the Globe

Manufacturer		
AAC Clyde Space	Information Satellite Systems Reshetnev Co.	Puli Space Technologies
Adcole Maryland Aerospace	Innovative Solutions in Space (ISISpace)	Pumpkin Space Systems
Aerospacelab	Inovor Technologies	QinetiQ
Agencia Espacial Civil Ecuatoriana (EXA)–Ecuadorian Civilian Space Agency	Intuitive Machines	Rafael
Airbus	INVAP	RAM Co.
Alba Orbital	Israel Aerospace Industries (IAI)	Reaktor Space Lab
Alén Space	Jet Propulsion Laboratory (JPL)	Reshetnev Information Satellite Systems Co.
Amazon	Johns Hopkins University Applied Physics Laboratory	Rocket Lab
Analytical Space	Khrunichev	Roscosmos
Antrix	Korea Aerospace Industries	Russian Space Systems
ARGOTEC	Kyushu Institute of Technology (Kyutech)	Satrec Initiative
Artemis Space	Lavochkin Associates	SatRevolution
Asia Pacific Satellite Inc. (APSI)	LEO earth observation satellites	Saturn Satellite Networks
AST&Science	Leonardo	Scaled Composites
Astranis Space Technologies	LeoStella	SCS Aerospace Group (SCSAG)
Astro Digital	L'Garde	SCS Space

Manufacturer		
Astrobotic	Libre Space Foundation	Shanghai Academy of Spaceflight Technology (SAST)
Astrocast	LinkSpace	Sierra Nevada Corp.
Astrome Technologies	Lockheed Martin	SITAEL
Aurora Space	Loft Orbital	Slovenian Centre of Excellence for Space Sciences and Technologies (SPACE-SI)
Axelspace	Lunar8	Space Advisory Co. (SAC)
Azista	Lunasonde	Space Applications Centre (SAC)
Aztra Labs	LuxSpace	Space Dynamics Laboratory
Ball Aerospace	Magellan	Space Engineering Research Center (SERC)
Berlin Space Technologies (BST)	Masten Space Systems	Space Flight Laboratory (SFL)
Bigelow Aerospace	Maxar Technologies	Space Information Laboratories (SIL)
BlackSky Global	MDA	Space Inventor
Blue Canyon Technologies (BCT)	Microsat Systems Canada Inc. (MSCI)	Space Research Institute (IKI)
Boeing	Microspace	Space Tango
Boreal Space	Millennium Space Systems	Spacebel
Canon Electronics	Mini-Cubes	Spacecraft Group, Brigham Young University
Capella Space	Mino Space	SpaceFab.U.S.
Celestia Aerospace	Mitsubishi Electric Corp.	SpaceIL
Central Research Institute for Machine Building (FGUP TSNIIMASH)	Mitsubishi Heavy Industries	Spacemaniac
Centre Spatial Universitaire de Grenoble (CSUG)	Mohammed bin Rashid Space Centre (MBRSC)	SpaceQuest
Centre Spatial Universitaire de Montpellier (CSUM)	Moog	Spaceteq
Chandah Space Technologies	Moon Express	Spacety
Chang Guang Satellite Technology (CGSTL)	n~ask	SpaceWorks
China Academy of Space Technology (CAST)	Nanoracks	SpaceX (Space Exploration Technologies)
China Aerospace Science and Industry Corp (CASIC)	Nanyang Technological University	Spire Global
China Great Wall Industry Corp. (CGWIC)	National Aeronautics and Space Administration (NASA)	Sputnix
Circle Aerospace	National Space Organisation (NSPO)	SRI International
Cislunar Explorers	National University of Singapore	SSL
Dassault Aviation	Naval Research Laboratory	ST Engineering
DEWC Systems	NEC	Stara Space
Dynmon	Nelson Mandela University	Surrey Satellite Technology Ltd. (SSTL)
Earth imaging; remote sensing; technology demonstration; astronomy	Nexeya	Surrey Space Centre
Elecnor Deimos	Northrop Grumman	Swarm Technologies

Manufacturer		
Emxys	NovaWurks	T STAR (Texas Space Technology Applications and Research)
Energia	OHB Italia	Terma
Exseed Space Innovations	OHB SE	Terran Orbital
Fleet Space Technologies	OHB Sweden	Thales Group
Fossa Systems	OHB System	The Spaceship Co.
GAUSS (Group of Astrodynamics for the Use of Space Systems)	OK Space	Thorium Space
General Atomics	Old Dominion University (ODU)	ThumbSat
German Orbital Systems	Olis Robotics	Tiger Innovations
GOSPACE Technologies	OneWeb Satellites	Tsniimash
GRiP	Open Cosmos	Turkish Aerospace Industries (TAI)
GUMUSH Aerospace and Defense	Orbital Loft	Tyvak Nano-Satellite Systems
Harris Corp.	Orbital Micro Systems (OMS)	Umbra Lab
Hawaii Space Flight Laboratory	Orbital Oracle Technologies (Orora Tech)	Universitat Wurzburg
Hedy-Anthiel Space Systems	ORBITBeyond	University College Dublin
Hemeria	Parabilis Space Technologies	University New South Wales, Canberra Space
Hera Systems	PES University	University of Florida, Department of Mechanical and Aerospace Engineering
Hertz Systems	Picosat Systems	University of Virginia (UVA)
Husky Satellite Lab	Picosats	UTIAS Space Flight Laboratory (SFL)
Hypercubes	Pixxel	ViaSat
Hypergiant Industries	Planetary Resources	Virginia Tech
ILC Dover	PlanetiQ	York Space Systems
Independence-X Aerospace	PocketSpacecraft.com	Yuzhmash
Indian Space Research Organisation (ISRO)	PTScientists	Yuzhnove State Design Office

Source: Space-Tech

Chapter 7

Market Breakdown by Region

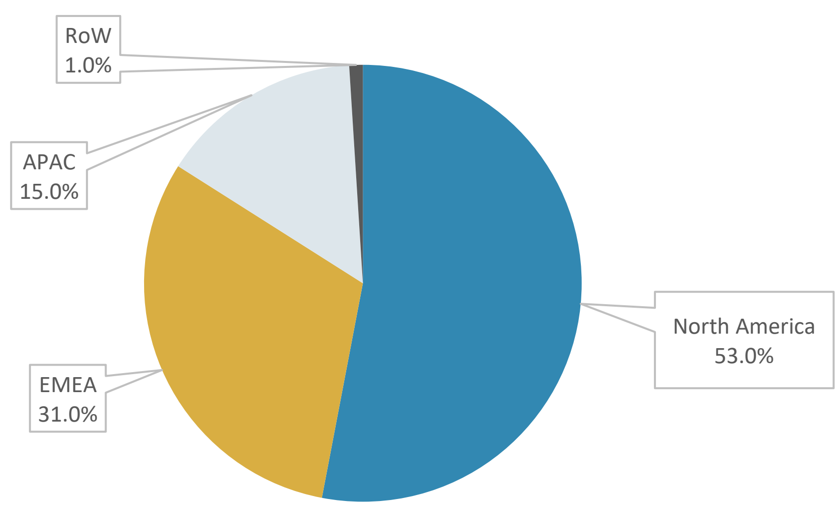
Chapter 7: Market Breakdown by Region

In this report the aerospace ceramics market is segmented into four regions: North America, Europe, Asia-Pacific, and Rest of the World (RoW). The Rest of the World includes the subregions of South America and the Middle East and Africa. The regional analysis includes key markets in the regions and respective market dynamics.

The aircraft manufacturing industry is geographically concentrated in North America and Europe, as the bulk of aircraft and component manufacturers are in these regions. It is expected that North America will remain the largest market for aerospace ceramics during the forecast period, with the defense aerospace segment driving its growth. As most of the aircraft and aircraft component manufacturing takes place in U.S., North America is already the top consumer of aerospace ceramics in all the aerospace segments. Canada is another key player in the region; however, its contribution is relatively small.

Europe is the second largest market for aerospace ceramics due to high demand from France, the U.K. and Germany. The region was hit severely by the COVID-19 pandemic and is expected to recover more slowly as compared to other regions. Asia-Pacific is a promising market for aerospace ceramics due to its growing domestic aircraft manufacturing industry.

Figure 26
Shares of Global Aerospace Industry, by Region, 2017
(%)



Source: Aero Dynamic Advisory, 2018

Table 37
Aerospace Business Attractiveness

Country	Rank	Cost	Labor	Infrastructure	Industry	Geopolitical Risk	Economy	Tax Policy
U.S.	1	4	3	8	1	3	6	25
Singapore	2	15	6	4	2	14	11	7
Canada	3	3	1	20	6	4	31	19
South Korea	4	14	45	2	19	7	12	21
Japan	5	37	9	1	10	1	5	51
Australia	6	1	27	17	24	6	18	28
U.K.	7	20	5	10	17	10	16	27
Germany	8	43	7	7	5	2	7	46
Switzerland	9	13	15	14	25	15	9	20
Hongkong	10	21	24	3	39	34	29	2

Source: PwC

Table 38
Key Countries and Aircraft Manufacturers

Sr. No.	Country	Manufacturer
1	U.S.	Boeing, Lockheed Martin, Sikorsky Aircraft, Gulfstream Aerospace
2	France	Airbus, Dassault Aviation, ATR, Arianespace
3	Germany	Airbus
4	Canada	Bombardier
5	U.K.	Airbus
6	Brazil	Embraer
7	Spain	Airbus
8	Italy	Leonardo Helicopters, ATR, Piaggio Aerospace
9	China	COMAC
10	Switzerland	Pilatus Aircraft
11	India	Hindustan Aircraft
12	Japan	Kawasaki Aircraft Industries, Mitsubishi Aircraft Corp., Mitsubishi Heavy Industries
13	Russia	PZL Mielec, PZL-Świdnik
14	Austria	United Aircraft Corp., Russian Helicopters, Energia
15	Saudi Arabia	Diamond Aircraft Industries
16	Australia	Brumby Aircraft Australia

Source: Wikipedia

As many countries are battling with the variants of corona and mucormycosis, it is expected the aerospace industry will recover slowly in the initial phase of the forecast period. With a decreased number of passengers and stricter safety regulations, the best way for commercial aerospace players to stem losses is to increase profit margins with available traffic. This puts the idea of increasing the fuel efficiency of aircraft in the spotlight. The primary solution to this is to reduce the weight of aerostructures by replacing heavy components (mostly metals) with lighter materials. Though the aerospace industry has already been investing significant money and effort into the development of lightweight materials, the hit from pandemic is expected to put these activities into high gear, thereby increasing the adoption of ceramics and composites in more structural applications in the aerospace industry. These developments will drive the demand for ceramics and composites during the forecast period.

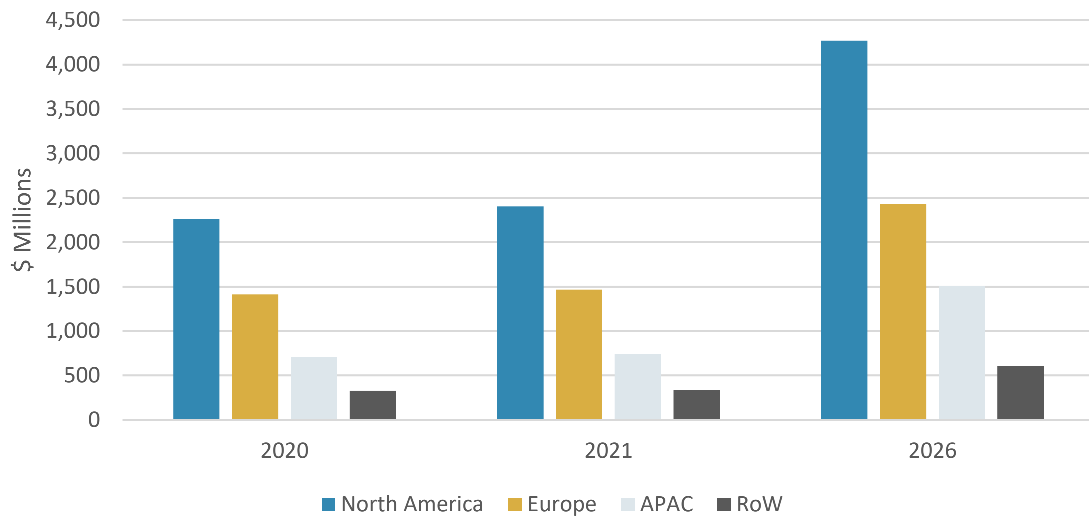
This chapter discusses regional trends in detail.

Table 39
Global Market for Aerospace Ceramics, by Region, Through 2026
($ Millions)

Region	2020	2021	2026	CAGR% 2021–2026
North America	2,260.2	2,404.4	4,267.6	12.2
Europe	1,412.6	1,466.3	2,430.0	10.6
APAC	706.3	740.5	1,506.6	15.3
RoW	329.6	339.5	604.3	12.2
Total	4,708.7	4,950.7	8,808.5	12.2

Source: BCC Research

Figure 27
Global Market for Aerospace Ceramics, by Region, 2021–2026
($ Millions)



Source: BCC Research

North America

In this study, North America includes the United States and Canada. The U.S. dominates the regional as well as global aerospace manufacturing industry and also leads in ceramics and composites consumption. The U.S. accounts for more than 90% of the regional market. Many leading manufacturers of aerostructures and jet engines are headquartered in U.S. Also, most of their production facilities are situated in this region.

The North American aerospace industry covers nearly the complete value chain of aerospace products. The region itself is a leading consumer of aircraft in the commercial, military, private, and space segments. The region also leads in the exports of aircraft-related products, with the U.S. contributing more than a 40% share in global exports. Increasing demand for commercial and military aircraft across the globe will boost the aircraft production in the region due to presence of leading companies such as Boeing, Lockheed Martin Corp., and Northrop Grumman. In turn, this will increase demand for ceramics and composites in the region.

Table 40
Global Aerospace Product Exports, by Top 15 Countries, 2019
($ Billions/%)

Sr. No.	Country	Export Value ($ Billions)	Share of Total Aerospace Product Exports (%)
1	U.S.	136.0	40.9
2	France	53.5	16.1
3	Germany	42.3	12.7
4	U.K.	18.3	5.5
5	Canada	11.3	3.4
6	Singapore	8.0	2.4
7	Spain	7.1	2.1
8	Italy	4.9	1.5
9	Ireland	4.8	1.4
10	Japan	4.5	1.4
11	China	3.9	1.2
12	Brazil	3.7	1.1
13	Israel	2.5	0.7
14	South Korea	2.4	0.7
15	Kuwait	2.4	0.7

Source: World's Top Exports

Table 41
North American Market for Aerospace Ceramics, by Country, Through 2026
($ Millions)

Country	2020	2021	2026	CAGR% 2021–2026
U.S.	1,921.2	2,049.3	3,655.9	12.3
Canada	339.0	355.1	611.7	11.5
Total	2,260.2	2,404.4	4,267.6	12.2

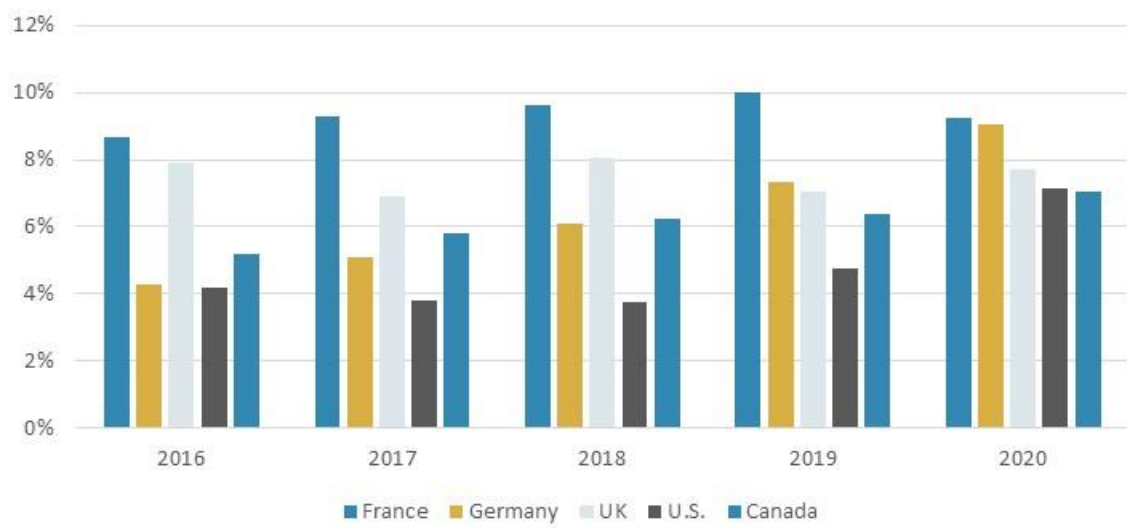
Source: BCC Research

Table 42
North American Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	1,356.1	1,421.9	1,833.1	5.2
Defense	745.9	809.7	1,531.6	13.6
Space	158.2	172.8	902.9	39.2
Total	2,260.2	2,404.4	4,267.6	12.2

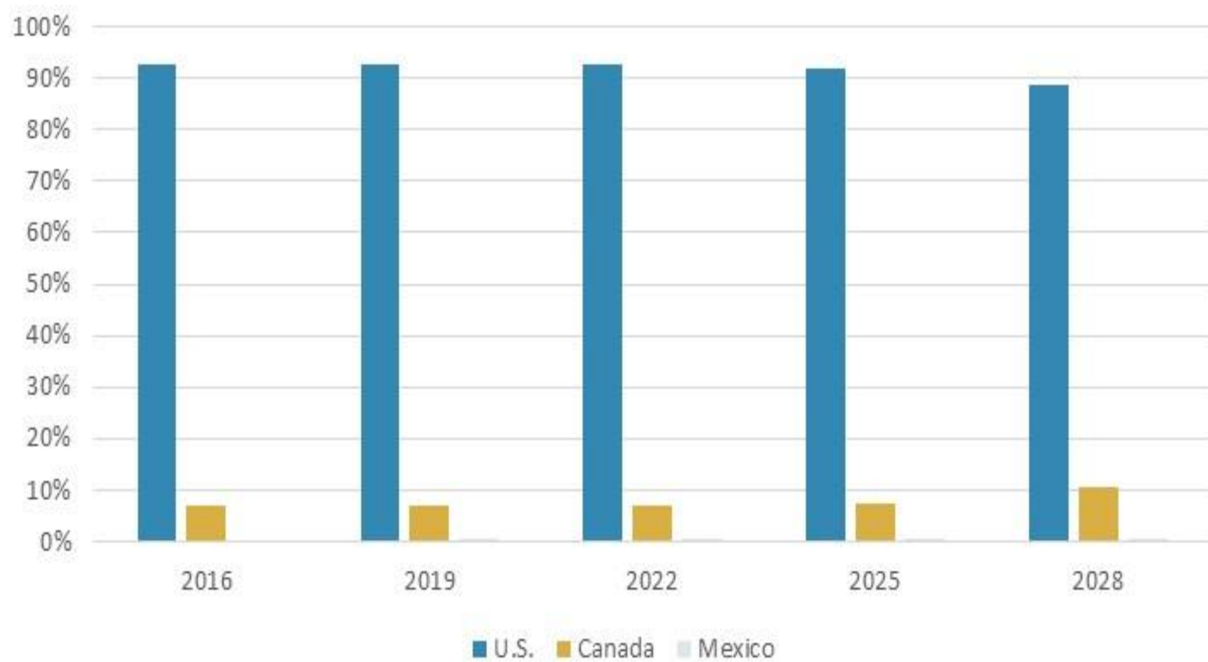
Source: BCC Research

Figure 28
Leading Importers of Aircraft, Spacecraft and Parts Thereof Exported by USMCA, by Country, 2016–2020
(%)



Source: International Trade Center, HS coed 88 Aircraft, spacecraft, and parts thereof

Figure 29
Aircraft, Spacecraft and Parts Thereof Exports from USCMA, by Country, 2016–2020
(%)



Source: Source: International Trade Center, HS coed 88 Aircraft, spacecraft, and parts thereof

The exports of aircrafts and related products from United States-Mexico-Canada (USMCA) are dominated by the U.S. with a share of more than 80%, followed by Canada. The top three markets for these exports are France, Germany and the U.K., which together accounted for more than 25% of the exports in 2020. The share of these markets increased from 20.9% in 2016 to 26.0% in 2020. The export share of leading APAC markets including China, Japan, Singapore, India, and Australia increased form 22.3% in 2016 to 25.1% in 2020. The increasing share of exports to other regions provides a potential for growth in North America production of aircraft and related products. In turn, this will increase the demand for ceramics and composites in aerospace applications in the region.

U.S.

The U.S. plays a huge role in the global as well as regional aerospace ceramics market. The country is home to many leading companies that manufacture aerospace components, aerostructures, engines, landing gear, and spacecraft. Some of the key players in the aerospace industry in the U.S. are Boeing, Lockheed Martin, Northrop Grumman, Honeywell, Hexcel, and Pratt & Whitney.

Table 43
U.S. Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	1,152.7	1,210.3	1,566.9	5.3
Defense	634.0	691.1	1,313.1	13.7
Space	134.5	147.9	775.9	39.3
Total	1,921.2	2,049.3	3,655.9	12.3

Source: BCC Research

The following table shows the leading destinations for U.S. exports of aircraft, spacecraft and parts thereof:

Table 44
Top Six Destinations for U.S. Exported Aircraft, Spacecraft and Parts Thereof, 2016–2020
($ Millions)

Importer	2016	2017	2018	2019	2020
Germany	5,999.9	7,080.8	8,903.3	10,359.9	8,100.8
France	12,257.1	12,918.7	14,152.8	14,607.5	8,053.2
U.K.	10,977.8	9,384.0	11,811.9	10,076.0	6,641.0
Canada	7,498.1	8,209.5	9,397.4	9,452.4	6,395.2
Brazil	4,812.6	5,450.7	6,078.5	6,956.2	4,884.9
China	14,578.0	16,265.6	18,221.9	10,460.0	4,399.2

Source: ITC, HS code 88

Boeing is the global leader in commercial aircraft production, and it is also expanding its business in the military and space segments. The company leads the ceramics and composites demand in the U.S. in the commercial aerospace segment. Boeing has been increasing the share of composites in its aircraft models over the years, leveraging their light weight and high-strength characteristics. In 2020, Boeing faced strong headwinds due to the grounding of its 737 Max, weaker demand for the 777X and the effects of the COVID-19 pandemic. The company postponed its 777X production plans to 2022,Twhich will decrease the potential growth rate for ceramics in the commercial aerospace segment in the country. Though the 737 Max completed its recertification in 2020, Boeing's deliveries dropped by more than 55%, which resulted in supply chain disruption across the aerospace industry And also drastically decreased demand for ceramics and composites in the commercial aerospace segment in 2020.

The defense aerospace segment consists of aircraft from Boeing, Lockheed Martin, Northrup Grumman, Bell, and other suppliers. Following are some of the key aircraft manufactured by these companies.

Table 45
Key Military Aircrafts Manufactured in the U.S.

Segment	Company	Army	Navy and USMC	Air Force
Fixed Wing	Boeing	–	F/A-18 Hornet/Super Hornet, P-8 Poseidon, EA-18G Growler, E-6 Mercury, AV-8B Harrier II	A-10 Thunderbolt II, B-52 Stratofortress, B-1 Lancer, C-17 Globemaster III, E-3 Sentry Command Post, F-15 Eagle, KC-46 Pegasus, VC-25, T-7A Red Hawk
	Lockheed Martin	–	F-35B/C Lightning II, P-3 Orion/ARIES	C-130 Hercules/Compass Call, F-16 Fighting Falcon, F-22 Raptor, U-2 Dragon Lady, F-35A Lightning II, C-5 Galaxy
	Northrop Grumman	–	E-2D Advanced Hawkeye	B-2 Spirit, B-21 Raider, E-8 Joint STARS
Rotary Wing	Airbus	UH-72A Lakota	UH-72A Lakota	–
	Bell Boeing	–	CMV/MV-22B Osprey	CV-22B Osprey
	Bell Textron	–	AH-1Z Viper, UH-1Y Venom	--
	Boeing	AH-64 Apache, CH-47 Chinook	--	MH-139 Grey Wolf
	LM-Sikorsky	UH-60 Black Hawk, VH-60N White Hawk	MH-53E, CH-53D/E/K H-60 Seahawk/Knighthawk, VH-92, VH-3D Sea King	HH-60 Pave Hawk
UAS	AeroVironment	RQ-11 Raven	RQ-12A WASP	RQ-20 Puma
	Boeing	--	RQ-21 Blackjack, MQ-25 Stingray	--
	FLIR	--	Black Hornet 3	--

Segment	Company	Army	Navy and USMC	Air Force
	General Atomics	MQ-1C Gray Eagle	--	MQ-9 Reaper
	Lockheed Martin	--	--	RQ-170 Sentinel
	Northrop Grumman	--	MQ-4C Triton, MQ-8B/C Fire Scout	--
	Textron	RQ-7B Shadow	----	--

Source: Industrial Capabilities Report to Congress | 2020 Annual Report

Six out of top 10 military aerospace companies of the world are from U.S., thus making the country the global leader in the military aircraft segment. The defense segment was not affected by COVID-19 as severely as the commercial segment. Indeed, the revenue of the top six military aircraft manufacturers in the country increased by 2% with increased foreign sales in 2020. Lockheed Martin, a leading manufacturer of military aircraft, saw a revenue increase of 9% due to increasing demand for its F-35. The company further plans to decrease the cost of F-35 to push the product demand higher in near future. Another key development in the defense segment was that in June 2021, Boeing successfully tested the MQ-21, a refueling UAV with U.S. Air Force. This drone UAV can transport fuel to fighter jets for midair fueling. For the UAV segment, China plays an important role as a leading supplier of composite components (fuselage), electric motors and PCSs to the U.S. The defense aerospace segment in the country will continue to be vibrant during the forecast period with the introduction of new aircraft, further development of UAVs and increasing demand for fighter jets around the globe. These trends will fuel the demand for ceramics and composites in the defense segment in the U.S.

Table 46
Top 15 Defense Aerospace Companies, Globally, 2020
($ Millions/% Change)

Rank	Company	Country	2020 Total Revenue ($ millions)	2020 Defense Revenue ($ millions)	%YoY Defense Revenue Change
1	Lockheed Martin	U.S.	65,398.00	62,562.00	11%
2	Raytheon Technologies	U.S.	65,000.00	42,000.00	N/A
3	Boeing	U.S.	58,158.00	32,400.00	-6%
4	Northrop Grumman	U.S.	36,799.00	31,400.00	10%
5	General Dynamics	U.S.	37,900.00	29,800.00	1%
6	Aviation Industry Corp. of China	China	67,911.42	25,468.59	2%
7	BAE Systems	U.K.	24,739.35	23,502.38	12%
8	China North Industries Group Corp. Ltd.	China	70,303.18	15,249.27	3%
9	L3Harris Technologies	U.S.	18,194.00	14,936.00	2%

Rank	Company	Country	2020 Total Revenue ($ millions)	2020 Defense Revenue ($ millions)	%YoY Defense Revenue Change
10	China State Shipbuilding Corp. Ltd.	China	66,911.23	13,379.35	28%
11	China Aerospace Science and Industry Corp.	China	37,702.80	12,060.26	0%
12	Airbus	Netherlands/France	56,970.41	12,004.28	7%
13	Leonardo	Italy	15,306.40	11,173.33	1%
14	China South Industries Group Corp.	China	34,499.29	10,697.68	21%
15	China Electronics Technology Group	China	33,977.45	10,465.75	3%

N/A= Not Available in source.

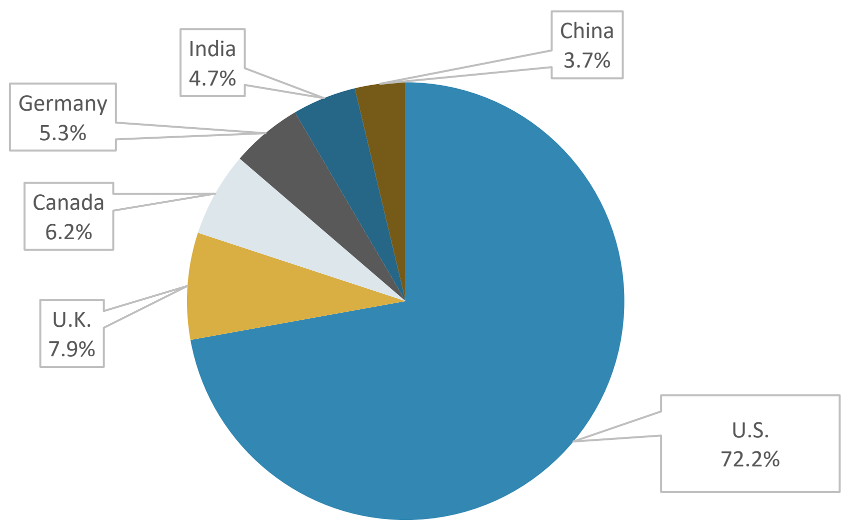
Source: Defense News

Pratt & Whitney is one of the few jet engine manufacturers in the world. The company opened a 60,000 sq. ft. engineering and development facility in California for CMC materials. GE Aviation, another jet engine manufacturer, uses CMC nozzles, fan stators, CMC shrouds, combustor liners, and fan blades manufactured in U.S. for its GE9X engine. This engine is the largest commercial jet engine in the world, and it is being used in Boeing 777X aircraft. As the production of the Boeing 777X is being pushed back, this will impact the demand for ceramics and composites in engine applications during the forecast period.

All aerospace companies are investing significant amounts in R&D to develop better materials in order to replace metals and alloys to achieve the goal of higher efficiency and safety of aircrafts. These efforts will result in increased usage of ceramics and composites in the respective applications.

In the global space and spacecraft industry as well, the U.S. has been a major contributor in terms of technological advancements and production capacity. The government budget and investments in the space sector far exceeds that of other countries in the world. The country ranks first in terms of governmental space budget, followed by China, which has a budget only one-seventh as large as the U.S. In terms of number of space tech companies, the U.S. space industry comprises more than 50% of global companies.

Figure 30
Shares of Global Space Tech Companies, by Geography, 2021
(%)



Source: Space Tech Analysis

The National Aeronautics and Space Administration (NASA), a national agency of the U.S., has been collaborating with other countries, especially Russia, for certain space operations. During the period of 2011 to 2020, the U.S. used Russia's Soyuz spacecraft to get its astronauts to the International Space Station. In May 2020, SpaceX, a U.S.-based private space transportation company, designed a cargo spacecraft named Dragon 1, thereby decreasing dependency on Russia. The increasing investments from private space companies such as Blue Origin, SpaceX, and Virgin Galactic will boost domestic production of spacecraft in the U.S., thereby increasing demand for ceramics and composites in the country.

Canada

Canada ranks among the top five aerospace markets in the world, with around 70% of the industry catering to the aircraft manufacturing segment. The Canadian aerospace industry mainly focuses on the single aisle, short-to-mid range category of passenger aircraft. The aerospace production activities in the country are concentrated in the city of Montréal, making it the world's third largest aerospace hub after Seattle, U.S. and Toulouse, France. Some of the key players in the country are Bombardier, Bell Textron, Pratt & Whitney Canada, L-3 Harris, Safran, Goodrich, Boeing, GE, Rolls Royce, and Lockheed Martin. Bombardier is headquartered in Montreal and is a key player in regional aircraft manufacturing industry.

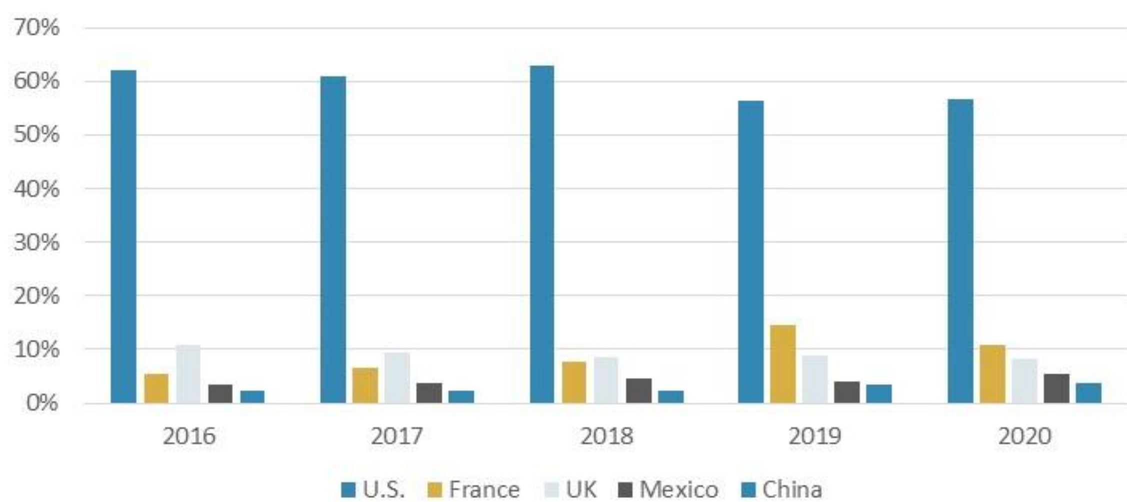
Table 47
Canadian Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	203.4	211.6	266.2	4.7
Defense	111.9	118.6	218.5	13.0
Space	23.7	24.9	127.0	38.5
Total	339.0	355.1	611.7	11.5

Source: BCC Research

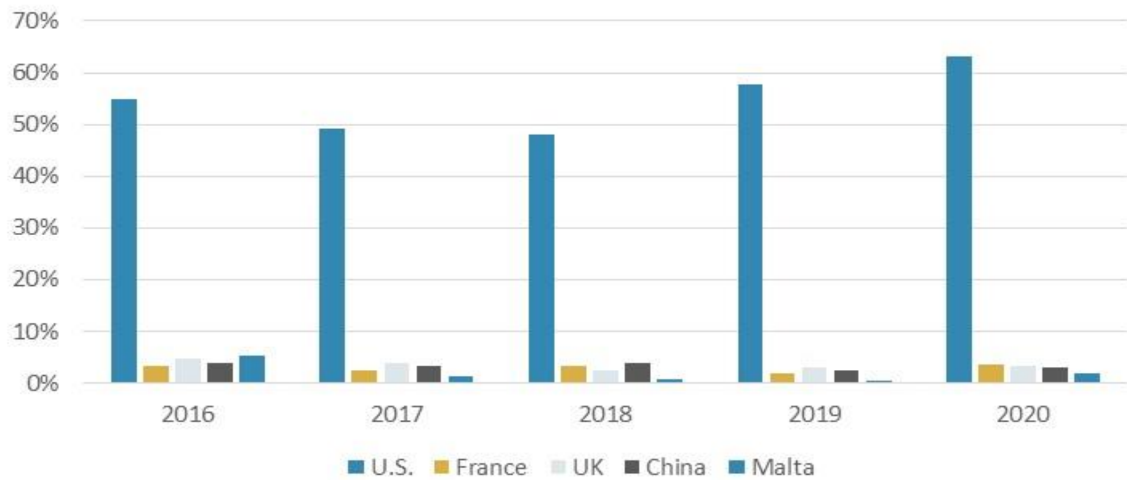
The domestic aerospace industry in Canada is capable of designing and manufacturing commercial aircrafts, gas turbine engines, flight simulator systems, and landing gears. The industry also caters to the demand for aerostructures and components made of advanced materials, including ceramics and composites. The Canadian aerospace industry predominantly focuses on exports, primarily to the U.S. and European countries. However, the industry has always been a leading destination of aircraft and components from the U.S.

Figure 31
Top Exporters of Aircraft, Spacecraft and Parts Thereof to Canada, by Country, 2016–2020
(%)



Source: ITC, HS Code 88

Figure 32
Top Destinations of Aircraft, Spacecraft and Parts Thereof Exported from Canada, by Country, 2016–2020
(%)



Source: ITC, HS Code 88

Table 48
Canadian Aerospace Manufacturing Industry, 2017–2020
($ Millions)

Metric	2017	2018	2019 (Estimated)	2020 (Estimated)
Total local production	22,368	23,900	24,081	22,000
Total exports	12,242	12,700	13,150	12,400
Total imports	11,331	11,746	12,200	11,500
Imports from the U.S.	9,248	9,955	10,539	9,942
Total market size	21,457	22,255	23,131	21,100

Source: International Trade Administration

Table 49
Key Companies Manufacturing Composite Components in Canada

Composite Bonding	Composite Ducting and Fairings	Composite Fabrication
Airbus	Airbus	Airbus
Avior Integrated Products Inc.	Avior Integrated Products Inc.	Avior Integrated Products Inc.
Bombardier	Burloak Technologies, a division of Samuel	Bombardier
Celestica	Flexibülb Inc.	Celestica
Flexibülb Inc.	Javelin Technologies Inc.	Field Aerospace
Héroux-Devtek Inc.	KF Aerospace	Flexibülb Inc.
IMP Aerospace and Defence	Magellan Aerospace	Garrtech Inc.
Magellan Aerospace	Patlon Aircraft and Industries Ltd.	IMP Aerospace and Defence
Nasmyth Group Ltd.	Safran Group	Javelin Technologies Inc.
National Research Council of Canada	Solaxis Ingenious Manufacturing Inc.	Leonardo
Providence Group	Stelia North America	Magellan Aerospace
Safran Group	–	National Research Council of Canada
StandardAero	–	Patlon Aircraft and Industries Ltd.
Stelia North America	–	Safran Group
–	–	Stelia North America

Source: Aerospace Industries Association of Canada

Europe

Several countries in Europe, notably Germany, France, the U.K., and Italy, are home to leading manufacturers and consumers of aerostructures and components made from ceramics and composites. Globally, the region ranks second in terms of aircraft production and exports. Aircraft production in the region is mostly concentrated in France, Germany, the U.K., and Italy, while Russia and Spain also contribute significantly to the regional aerospace industry. In this study, France, Germany and the U.K. are identified as leading consumers of aerospace ceramics; other countries considered are Italy, Russia and Spain.

France is the largest manufacturer consumer of aerostructures and components in the region, followed by the U.K. and Germany. The regional market is characterized by the presence of leading global players in commercial aircraft (Airbus), jet engine manufacturers (Roll Royce) and military aircraft (Dassault Aviation, BAE Systems). These players cater to respective demand from round the world and mostly locate their supply chain in the region, thereby driving the demand for ceramics and composites in the region.

Table 50
European Market for Aerospace Ceramics, by Country, Through 2026
($ Millions)

Country	2020	2021	2026	CAGR% 2021–2026
U.K.	353.1	364.3	578.9	9.7
France	635.7	664.6	1,086.5	10.3
Germany	183.7	189.6	308.7	10.2
Rest of Europe	240.1	247.8	455.9	13.0
Total	1,412.6	1,466.3	2,430.0	10.6

Source: BCC Research

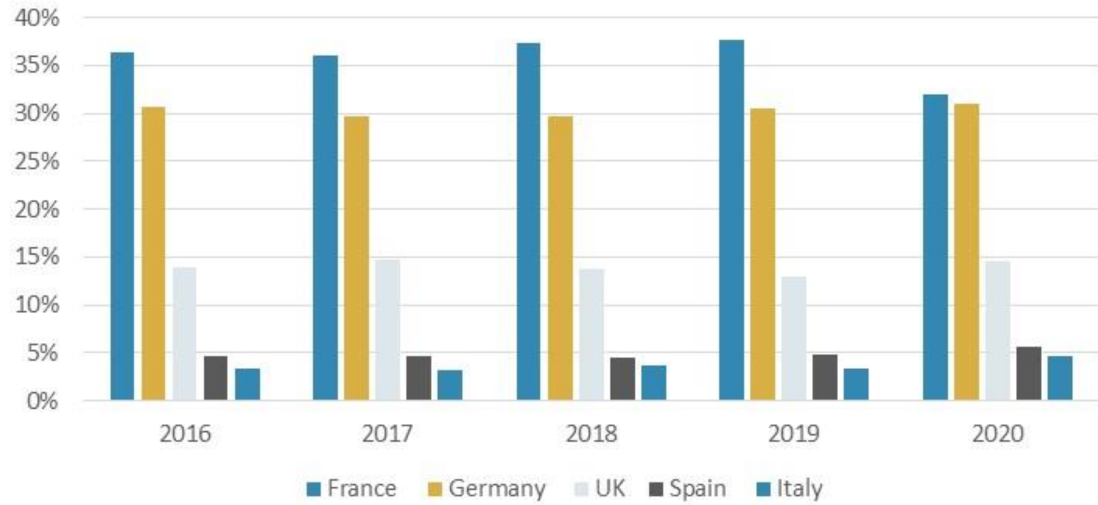
Table 51
European Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	914.7	946.2	1,178.8	4.5
Defense	404.5	424.6	777.5	12.9
Space	93.4	95.5	473.7	37.8
Total	1,412.6	1,466.4	2,430.0	10.6

Source: BCC Research

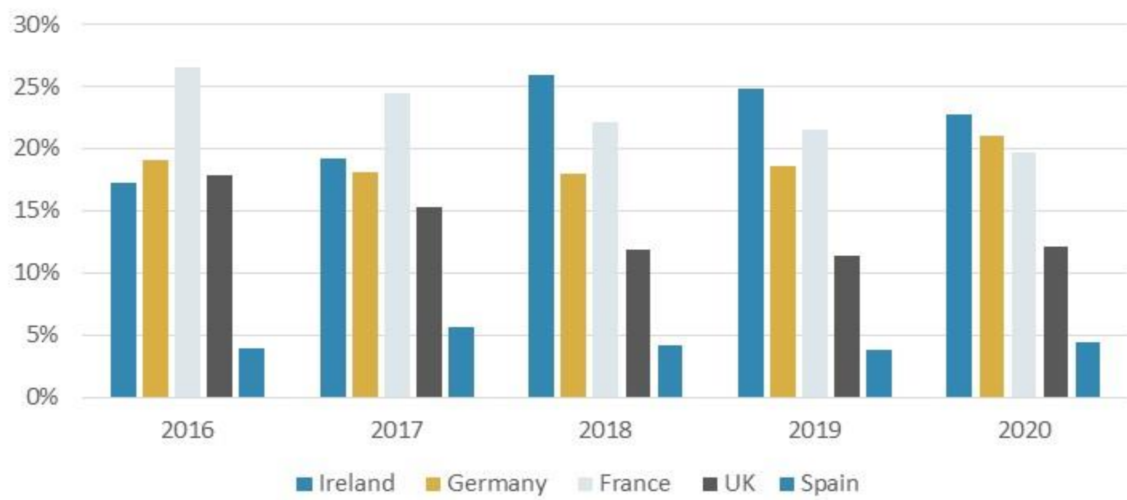
France leads the region in the export of aircraft, spacecraft and parts, closely followed by Germany. These countries accounted for a share of 63% in total aerospace-related exports from the EU in 2020. The key destinations for these exports are France, the U.S. and Germany, accounting for a combined share of 36% in 2020. The imports of aerospace-related products are led by Ireland, Germany and France.

Figure 33
Top Exporters of Aircraft, Spacecraft and Parts Thereof from the EU, by Country, 2016–2020
(%)



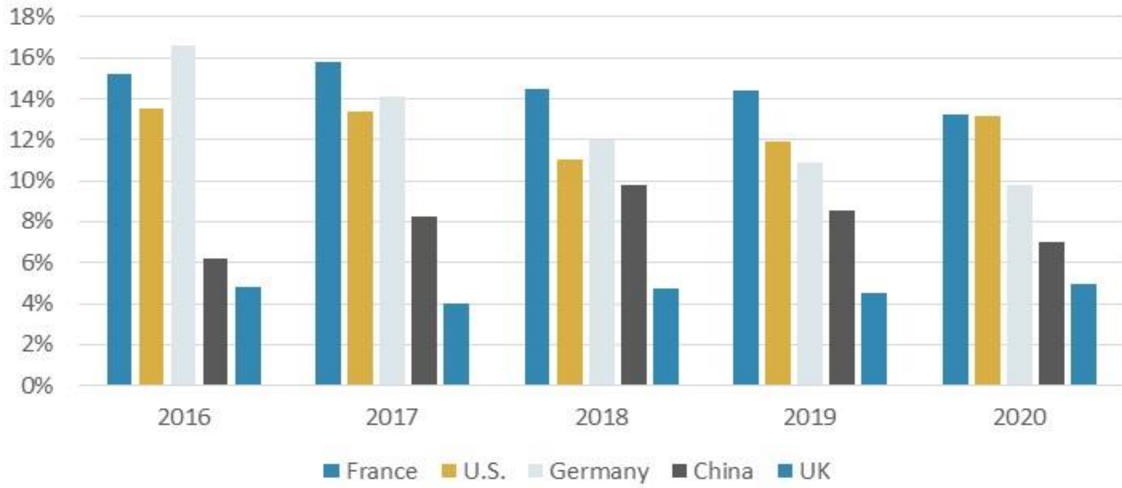
Source: ITC, HS Code 88

Figure 34
Shares of Aircraft, Spacecraft and Parts Thereof Imported into the EU, by Top Import Countries, 2016–2020
(%)



Source: ITC, HS Code 88

Figure 35
Shares of Aircraft, Spacecraft and Parts Thereof Exported from the EU, by Top Destination Countries, 2016–2020
(%)



Source: ITC, HS Code 88

The aerospace industry in Europe suffered huge losses due to the pandemic and supply chain disruption from order cancellations for Airbus aircraft. However, with recovering demand for regional jets and single-aisle commercial aircraft, it is estimated the market will reach pre-pandemic levels in the next five years.

France

France is the largest aircraft manufacturer in Europe, and ranks second globally, just after the U.S. The country is home to leading brands of commercial and defense aircraft manufacturers including Airbus, Dassault Aviation, Thales, and Daher, along with engine manufacturers such as Safran Aircraft Engines. These companies contribute to a large extent to the demand for ceramics and composites in the country.

Table 52
French Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	413.2	429.7	545.8	4.9
Defense	190.7	202.2	375.7	13.2
Space	31.8	32.7	165.0	38.2
Total	635.7	664.6	1,086.5	10.3

Source: BCC Research

The aerospace ceramics market in France is heavily dependent on production activities of Airbus and Dassault. In 2020, the industry experienced a steep drop in the production activities of commercial aircrafts especially due to reduced production from Airbus. The company plans to push back its production plans until 2022, thereby slowing down the demand for ceramics during the forecast period.

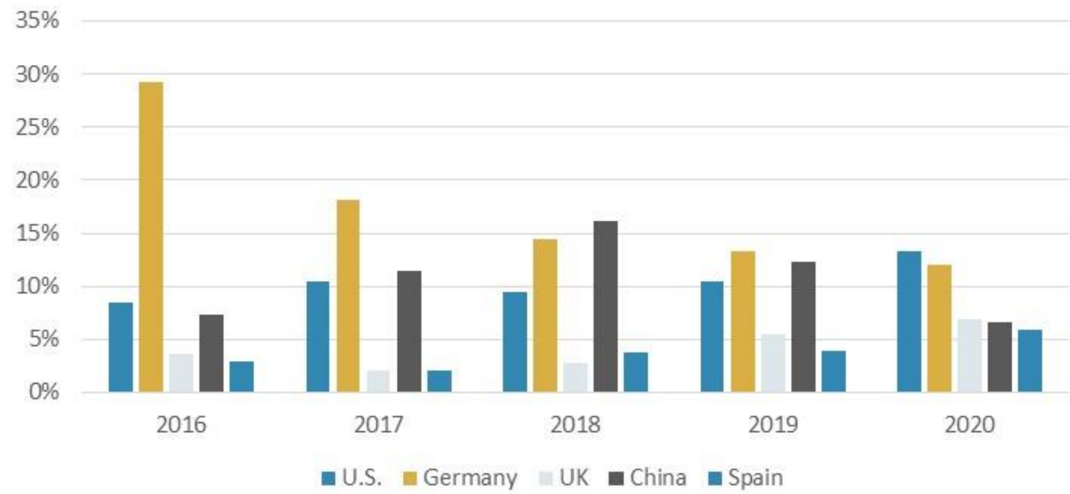
Table 53
French Aerospace Industry, 2017–2019
($ Billions)

	2017	2018	2019
Local Production	54.92	59.51	60.20
Exports	46.68	50.69	50.57
Imports	23.62	20.78	20.57
Imports from the U.S.	5.23	3.58	3.85
Market Size	31.86	29.70	30.20

Source: International Trade Administration (all values are estimated in the source)

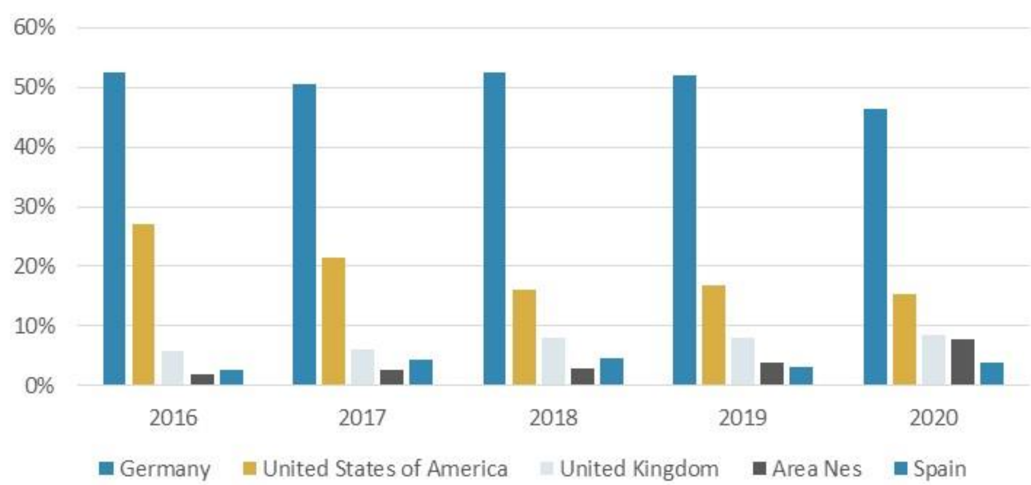
France is a leading exporter of aircraft, spacecraft and parts in the global market, with the U.S. and Germany being the top destinations for exports. Germany contributes the largest share of imports of aircraft and parts into France.

Figure 36
Top Destinations for Aircraft, Spacecraft and Parts Thereof Exported from France, 2016–2020
(%)



Source: ITA, HS Code 88

Figure 37
Shares of Aircraft, Spacecraft and Parts Thereof Imported into France, by Top Source Countries, 2016–2020
(%)



Source: ITA, HS code 88

U.K.

The U.K. is the second largest market for aerospace ceramics in Europe, with proven expertise in aerostructures, engines, propulsion systems, interiors, and MRO. The aerospace industry in U.K. covers a broad spectrum of aerospace products including parts for civil and military aircraft, turbojets, turbo-propellers, rotorcrafts, engine parts, and sub-assemblies. The assembly parts refer to wings, fuselages, undercarriages, de-icing equipment, safety belts, and brakes.

Table 54
U.K. Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	247.2	254.6	309.8	4.0
Defense	81.2	84.5	150.9	12.3
Space	24.7	25.2	118.2	36.2
Total	353.1	364.3	578.9	9.7

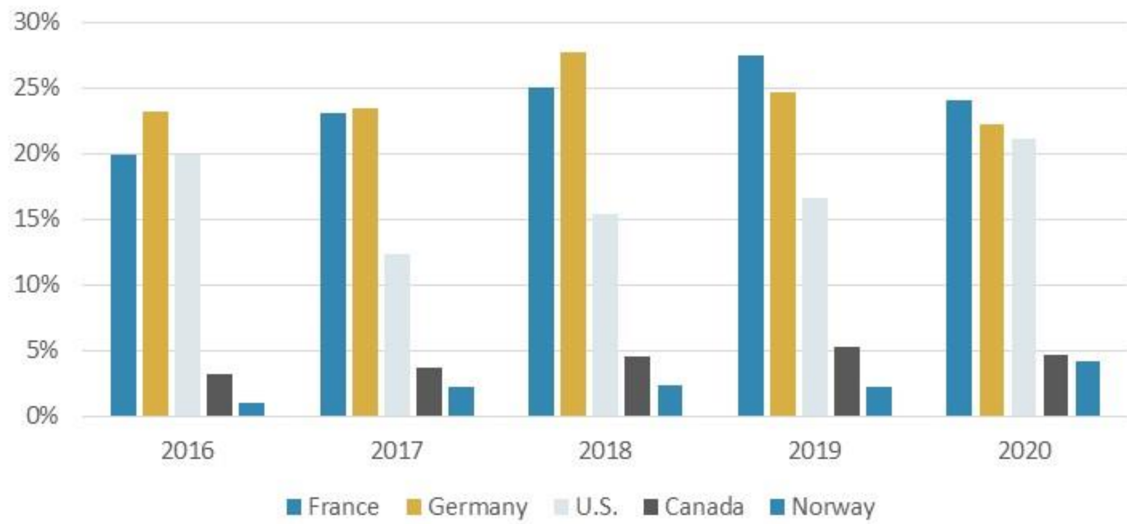
Source: BCC Research

Similar to France, the commercial aerospace industry in the U.K. is led by Airbus and engine manufacturers such as Rolls Royce and General Electric. The industry is increasingly investing in adoption of lightweight materials such as ceramics and composites to produce high-performance products to achieve sustainability goals. In 2018, the U.K. government facilitated composites production by investing £36.7 million in digital manufacturing technologies.

The U.K. aerospace industry comprises some of the top companies from the global aerospace industry contributing to the local aircraft production. Some of these companies are BAE Systems, Cobham, GKN, Meggitt, QinetiQ, Rolls-Royce, and Ultra Electronics, along with Boeing, Bombardier, Airbus, Leonardo, GE, Lockheed Martin, MBDA, Safran, and Thales.

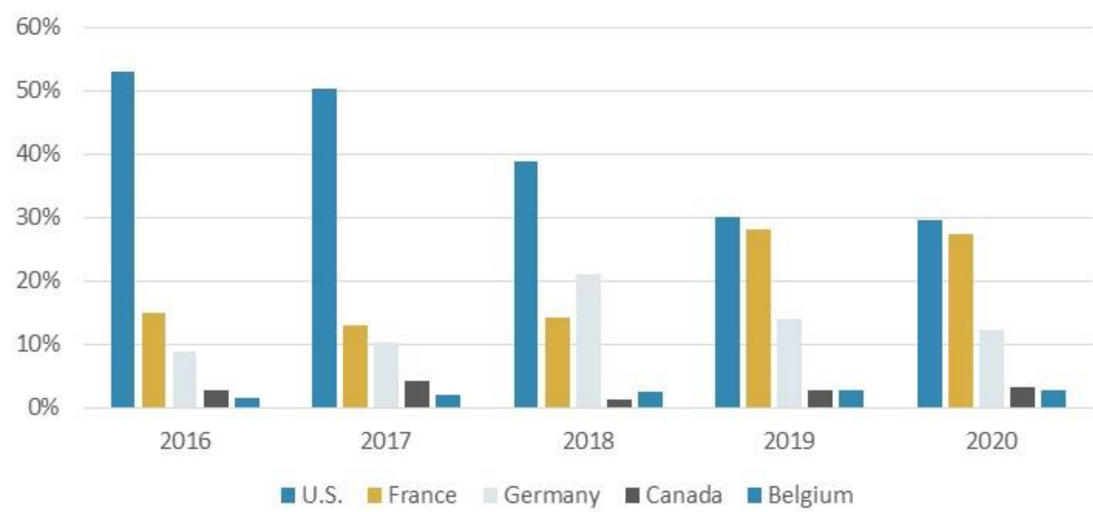
These companies drive the demand for ceramics and composites in the country. For instance, Airbus assembles the wings for all Airbus civil aircraft in the U.K. Also, Bombardier manufactures lightweight composite wings for its C Series. Boeing started a production facility in Sheffield near the Advanced Manufacturing Research Centre. The research center focuses on development of advanced materials such as composites.

Figure 38
Shares of Aircraft, Spacecraft and Parts Thereof Exported from the U.K., by Top Destination Countries, 2016–2020
(%)



Source: ITA, HS Code 88

Figure 39
Shares of Aircraft, Spacecraft and Parts Thereof Imported into the U.K., by Top Source Countries, 2016–2020
(%)



Source: ITA, HS code 88

Germany

The German aerospace industry is led by the commercial aircraft segment, which accounted for 70% of industry revenue in 2020. The country has a strong presence in the global commercial aircraft industry and claims that every sixth civil aircraft is delivered from Germany. The commercial aerospace segment lost one-third of its revenue in 2020 because of the pandemic, while the revenue of the military segment increased by 6%. The space industry experienced a drop of 15% in its turnover during 2020, primarily due to supply chain issues.

Table 55
German Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	110.2	113.5	137.4	3.9
Defense	60.6	63.0	111.6	12.1
Space	12.9	13.1	59.7	35.4
Total	183.7	189.6	308.7	10.2

Source: BCC Research

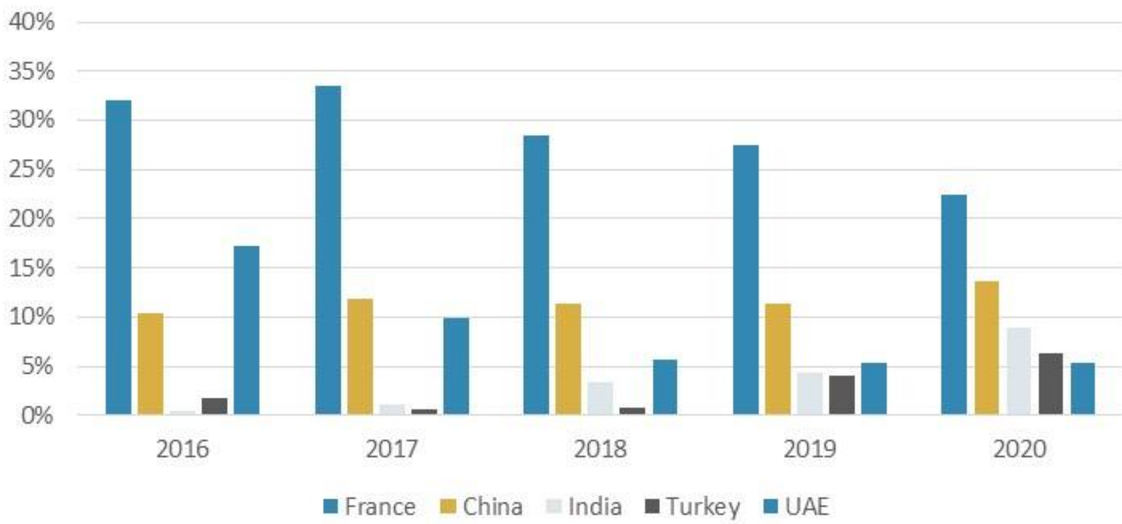
Table 56
German Aerospace Industry, 2016–2019
($ Millions)

Metric	2016	2017	2018	2019 (E)
Local production	41,509	45,188	47,240	46,740
Exports	29,886	33,439	35,902	35,522
Imports	19,810	18,824	18,621	18,462
Total market size	31,433	30,573	29,959	29,680

2019 (E)= Estimated values

Source: International Trade Administration

Figure 40
Top Destinations for Aircraft, Spacecraft and Parts Thereof Exported from Germany, 2016–2020
(%)



Source: ITA, HS Code 88

Figure 41
Top Sources for Aircraft, Spacecraft and Parts Thereof Imported into Germany, 2016–2020
(%)

Source: ITA, HS code 88

Rest of Europe

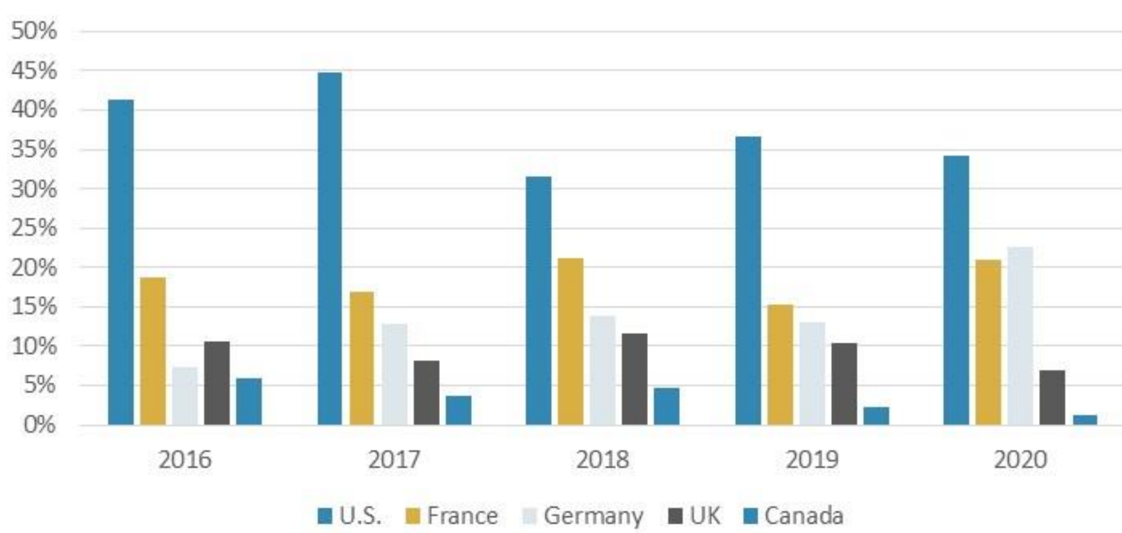
The rest of Europe region includes Italy, Spain and Russia. Italy and Spain manufacture commercial and business jets while Russia is known for military jet production. These countries have multiple aircraft manufacturers catering to a certain share of domestic demand in the commercial and defense segments. For instance, the Italian aerospace industry is comprised of Piaggio, Tecnam, Vulcan Air, BestShot Aircraft, and Alenia Aermacchi. Also, the Spain and Russia markets are led by Airbus and UAC, respectively.

Table 57
Rest of European Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	144.1	148.4	185.8	4.6
Defense	72.0	74.9	139.3	13.2
Space	24.0	24.5	130.8	39.8
Total	240.1	247.8	455.9	13.0

Source: BCC Research

Figure 42
Top Sources for Aircraft, Spacecraft and Parts Thereof Imported into the Rest of Europe, 2016–2020
(%)



Source: ITA, HS code 88

Asia-Pacific

Asia-Pacific (APAC) is the fastest growing market in aerospace ceramics due to rapidly growing domestic demand. China and Japan lead the regional aircraft manufacturing industry followed by South Korea. Japan has been the largest contributor in the industry, mainly catering to the demand from North America and Europe. However, now China and Japan both are aggressively investing in development of aerospace capabilities to compete with Airbus and Boeing. APAC is the largest manufacturer of CFRP, a composite widely used in the aerospace industry. This gives the region a strategic advantage in terms of raw material availability for aerostructure production.

Table 58
Asia-Pacific Market for Aerospace Ceramics, by Country, Through 2026
($ Millions)

Country	2020	2021	2026	CAGR% 2021–2026
Japan	317.9	324.7	631.0	14.2
China	226.0	246.4	552.4	17.5
South Korea	98.9	103.2	183.2	12.2
Rest of APAC	63.5	66.3	140.0	16.1
Total	706.3	740.5	1,506.6	15.3

Source: BCC Research

Table 59
Asia-Pacific Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	402.9	422.4	588.3	6.9
Defense	223.1	235.7	480.4	15.3
Space	80.3	82.5	438.0	39.6
Total	706.3	740.6	1,506.6	15.3

Source: BCC Research

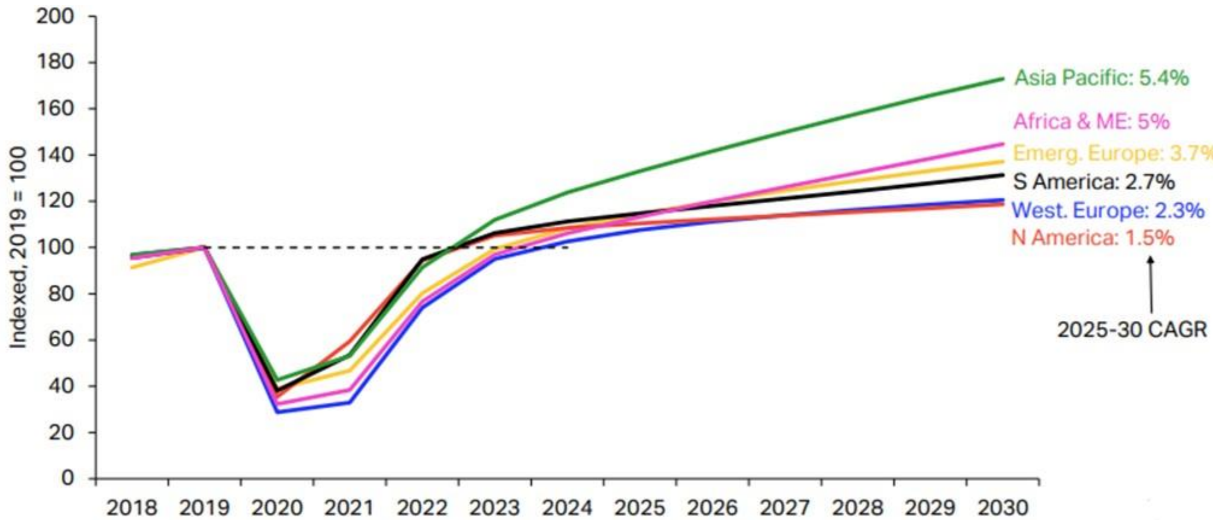
With a growing population, growing disposable income and increasing defense budgets in the region, the domestic market for airline service and aircraft have increased in the last decade in Asia-Pacific. The regional demand for such products and services are mainly driven by Japan, Australia, Singapore, and South Korea. However, the market in China and India is also growing due to a rising standard of living and high defense expenditures. Disposable income in China is expected to bounce back at a higher rate than the global average in 2021 and 2022, Which will help drive expenditures on regional air travel.

Table 60
Disposable Income Forecast, by Country, FY 2021–22

Country	Q2/21	Q3/21	Q4/21	Q1/22	Currency and Unit	% Change (Q2/21-Q1/22)
Bangladesh	66	68	80	80	BDT Mn	20.8%
Canada	1,354	1,371	1,382	1,370	CAD Bn	1.2%
China	44,519	44,604	46,289	46,289	CNY	4.0%
France	415	381	397	399	EUR Bn	-3.9%
Germany	546	537	541	553	EUR Bn	1.3%
India	245,001	223,292	214,067	212,869	INR Bn	-13.1%
Italy	313	303	304	307	EUR Bn	-2.2%
Japan	860	391	888	399	JPY Tho	-53.6%
South Korea	1,985,575	1,974,020	1,996,839	1,989,085	KRW Bn	7.1%
United Kingdom	433,373	391,831	384,980	395,345	GBP Mn	0.2%
United States	20,451	18,508	17,891	18,500	USD Bn	-8.8%

Source: Trading Economics

Figure 43
Global Air Passenger Recovery Forecast, by Region, 2018–2030
(%)



Source: IATA

Companies such as Airbus and Boeing are expanding their production capacity in APAC to leverage the rapid recovery during the forecast period. Also, domestic competitors such as Commercial Aircraft Corp. of China (COMAC) and Mitsubishi Aircraft Corp. have been strengthening their capabilities. With recovering domestic and international aircraft manufacturing activities, the local production for aircraft components and aerostructures will grow rapidly, which will increase demand for ceramics and composites in aerospace applications in the region at rates higher than the global average during the forecast period.

China

China globally ranks second in terms of its domestic aviation market and is soon expected to replace the U.S. at the top. The country is already one of the leading suppliers of components and aerostructures in APAC. The Chinese government is focusing on increasing its domestic aircraft production capacity to reduce dependency on U.S. based manufacturers. The government's plan "Made in China 2025," puts aerospace in the spotlight to leverage existing capabilities and build China as a trustworthy brand for aerospace products. With the government's support, Chinese manufacturer COMAC enjoyed stable orders from domestic airlines even during the pandemic. Three state-owned airlines canceled their orders to Boeing and Airbus while keeping orders to COMAC constant. Additionally, China's aircraft manufacturing industry growth has been boosted by the state's civil and military fusion strategy.

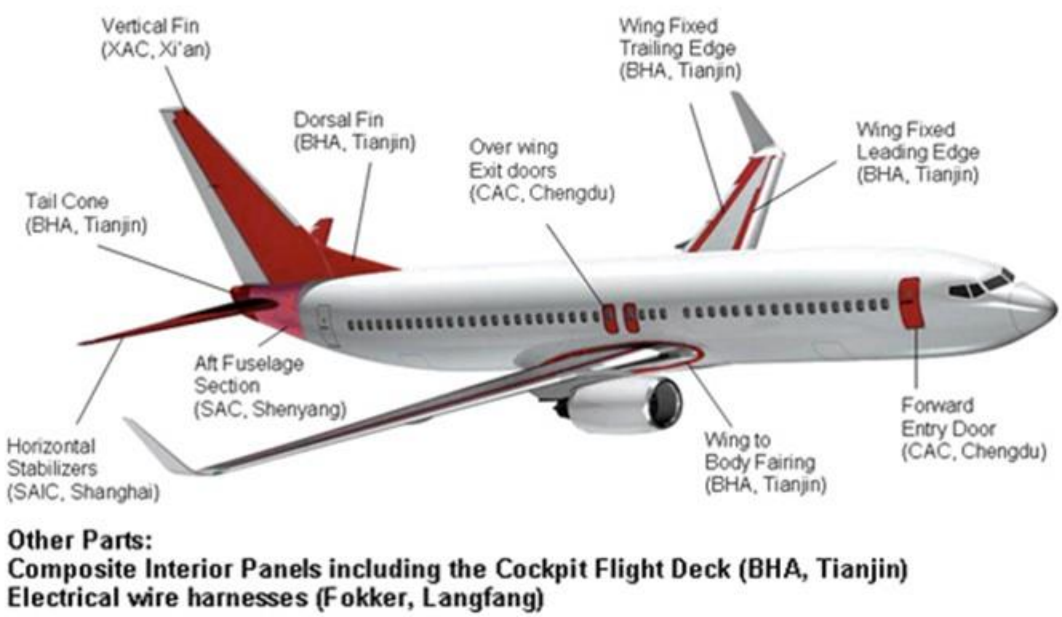
Table 61
Chinese Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	135.6	147.8	230.6	9.3
Defense	67.8	74.6	171.4	18.1
Space	22.6	24.0	150.4	44.3
Total	226.0	246.4	552.4	17.5

Source: BCC Research

COMAC caters the to the demand for commercial aircraft with three models, the C919, ARJ21 and CR929. These models cover the range of short-to-medium range turbofan and long-range widebody aircraft. The CR929 is a dual-aisle civil aircraft jointly developed by China and Russia.

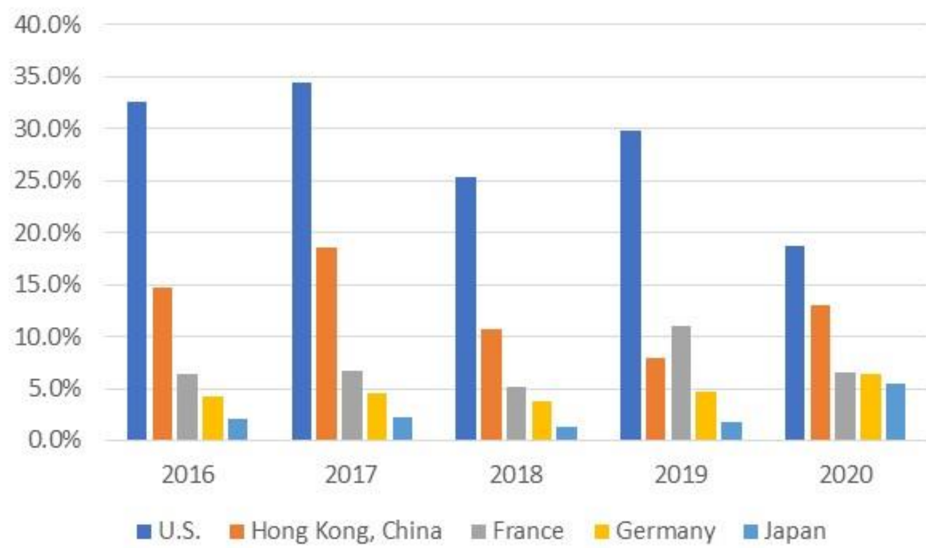
Figure 44
Boeing 737 Components Manufactured in China



Source: Council on Foreign Relations

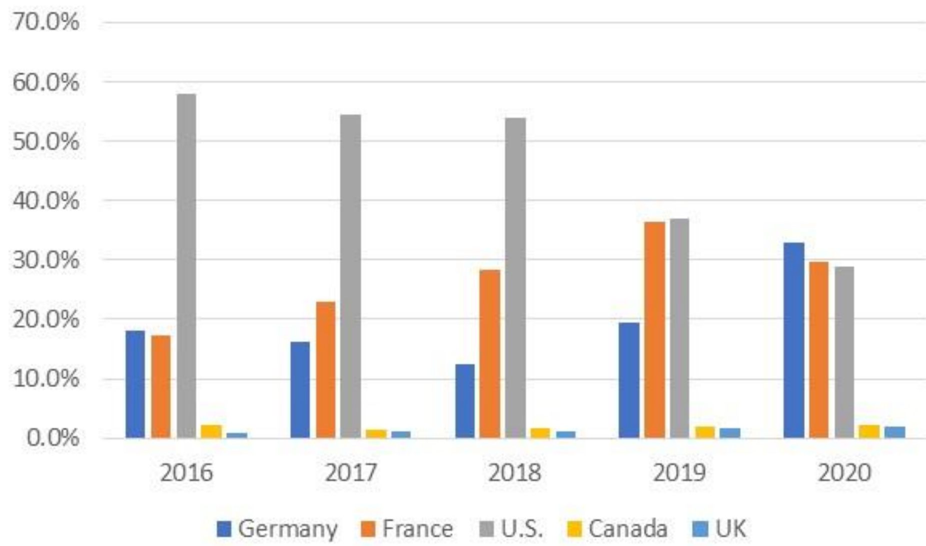
The U.S., France, Germany, and Japan are the top destinations of China's exports of aircraft, spacecraft and parts thereof over the past five years. Though the country has been significantly increasing its domestic production of aircraft components, it still imports components and aircraft from North America and Europe. The top five countries that export aircraft, spacecraft and parts to China are Germany, France, the U.S., Canada, and the U.K.

Figure 45
Top Destinations of Aircraft, Spacecraft and Parts Thereof Exported from China, 2016–2020
(%)



Source: ITA, HS code 88

Figure 46
Top Sources of Aircraft, Spacecraft and Parts Thereof Imported to China, 2016–2020
(%)



Source: ITA, HS code 88

Japan

In APAC, Japan is the largest market for aerospace ceramics. The country is a leading manufacturer of aerostructures and aerospace components for companies in the commercial as well as defense segments. The Japanese aerospace industry operates in three segments: aerostructures, engines and equipment. The aerostructure segment includes airframes and related parts and the engine segment refers to production and assembly of engine components.

Table 62
Japanese Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Space	47.7	48.2	232.4	37.0
Commercial	174.8	178.3	220.1	4.3
Defense	95.4	98.2	178.6	12.7
Total	317.9	324.7	631.0	14.2

Source: BCC Research

Table 63
Shares of Japanese Aerospace Industry, by Segment, 2018
(%)

Segment	Share (%)
Aerostructures	54
Engines	39
Equipment	7
Total	100

Source: Japanese Aerospace Industry 2020–2021

Table 64
Japanese Aerospace Industry Turnover, by Segment, 2018
(Billion Yen)

Segment	Turnover (Billion Yen)
Civil export	832
Civil Domestic	451
Defense	555
Space	290
Total	2,128

Source: Japanese Aerospace Industry 2020–2021

Japan's aerospace industry primarily started off with production of defense aircraft. Even now, the country manufactures some of the leading defense aircraft, such as the F-2 fighter, OH-1 observation helicopter, the T-4 and T-7 trainer, and the U.S.-2 search and rescue flying boat. However, the focus has shifted towards commercial and space vehicles over the last decade. The shift can be observed by increased employment and turnover of commercial aircraft and spacecraft segments. Japan plays a crucial role in the supply chain of leading commercial aircraft manufacturers Boeing and Airbus. The country plays a crucial role in production of the Boeing 767, 777, 777X, and 787; the Airbus A320, A330, A350 XWB, and A380; along with jet engines including the V2500, Trent1000, GEnx, GE9X, and PW1100G-JM. Japanese manufacturers contribute more than 20% of the main structural components of the Boeing 777X.

Like China, the aerospace industry players in Japan are trying to make the industry homegrown by developing and manufacturing commercial aircraft in the country. The Mitsubishi SpaceJet is one such attempt. This is an aircraft manufactured by Mitsubishi Aircraft Corp. to meet the demand for regional jets in the country. Considering the experience and expertise Japanese aircraft manufacturers, this trend can help shift the production hub from North America and Europe to Asian countries in coming years.

Following are some of the projects in the commercial aerospace segment in which the Japan aerospace industry plays a key role.

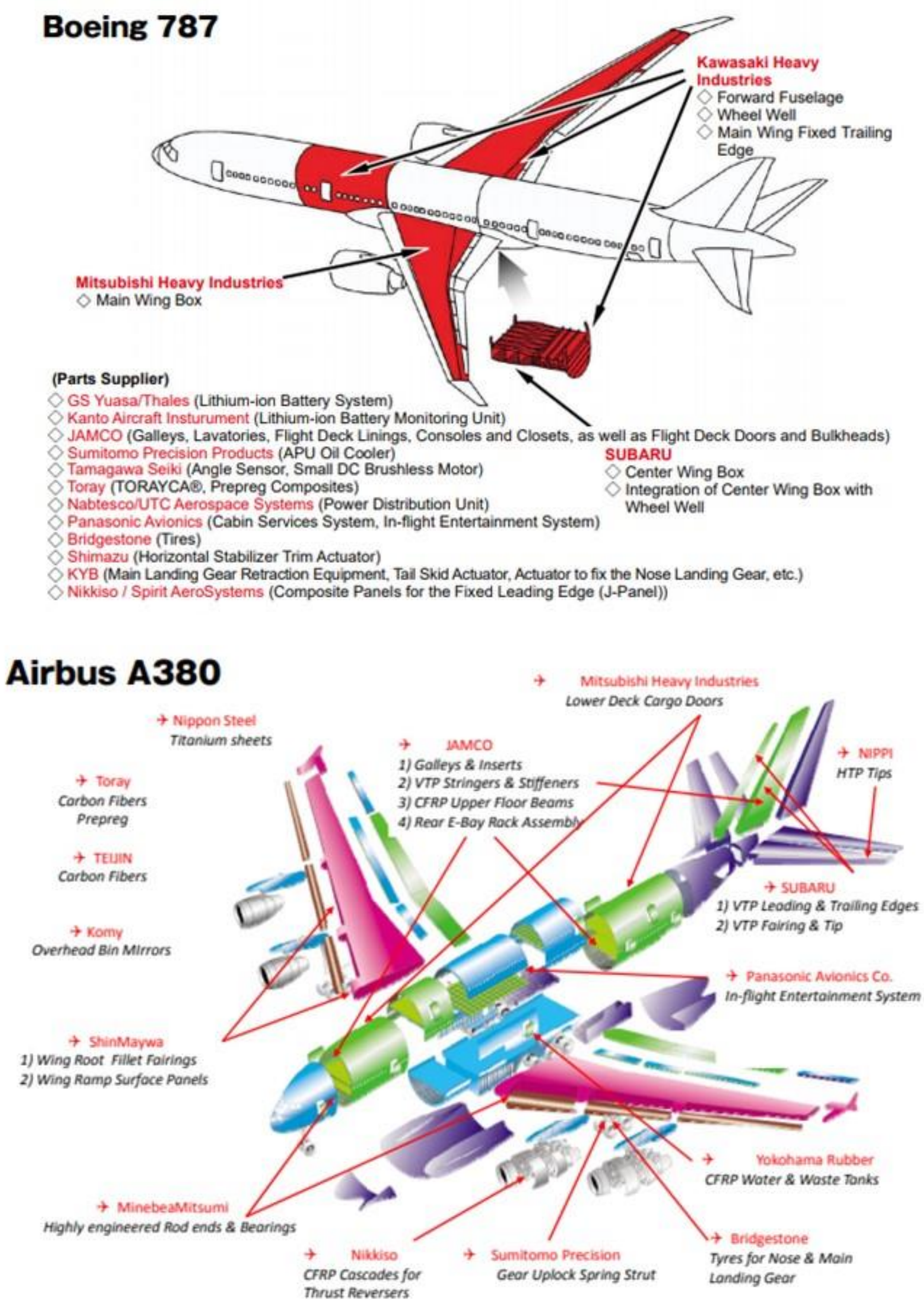
Table 65
Japan's Role in Key Commercial Aircraft and Rotorcraft Projects, 2020–2021

Project	Area of Participation	Scope of Participation
Boeing 767	Forward fuselage, aft fuselage and main landing gear door	15% program partner
Boeing 777, 777X	Centre section, center fuselage and aft fuselage	21% program partner
Boeing 787	Wings, center wings and front fuselage	35% program partner
Bombardier Challenger 350	Wings and main landing gear	Required Surveillance Performance
Bombardier G 5000/6000	Wings, center wings and center fuselage	Required Surveillance Performance
Bombardier CRJ 700/900	Nose and main landing gear system	Required Surveillance Performance
Embraer 170/190	Wings and center wings	Required Surveillance Performance
Gulfstream	Flaps and landing gear operation devices	Supplier
Airbus A380	Cargo doors, vertical stabilizer structure material, carbon fiber, and water tanks	Supplier
MD Helicopters MD902	Transmission	Production
AgustaWestland AW139	High-speed gearbox	Required Surveillance Performance

Required Surveillance Performance = A set of requirements for air traffic service provision, aircraft capability, and operations needed to support performance-based surveillance within a defined airspace.

Source: Japanese Aerospace Industry 2020-2021

Figure 47
Components of Boeing 787 and Airbus A380 Manufactured in Japan



Source: Japanese Aerospace Industry 2020-2021

With such a large bandwidth of aerospace products, Japan leads the regional market for aerospace ceramics. Some of the key composite products manufactured in the country are composite rotor crafts, main wings and center wing boxes along with fan castings and turbine blades. Also, the space industry in Japan provides launch vehicles, satellite systems, onboard sensors, and components to customers around the world. The industry has made successful launches of weather and communication satellites (HIMAWARI, SAKURA series and YURI series) using locally manufactured launch vehicles.

Table 66
Japan's Role in Key Commercial Aircraft Engine Projects, 2020–2021

Engine	Aircraft	Components Developed	Level of Participation
PW1100G-JM	A320 neo	Fans, low-pressure compressors modules, combustor, and low-pressure shafts	Program partner 23%
Trent1000	787	Mid-pressure modules, combustor modules and low-pressure turbine vanes	RSP 15.5%
GEnx	787	Low-pressure turbines, high-pressure compressors, shafts, and combustor cases	RSP 15% and subcontract
GP7200	A380	Coupling shaft	Subcontract
Trent900	A380	Low-pressure turbine blade	Subcontract
Trent500	A340	Mid- and low-pressure turbine vanes, compressor cases, and turbine cases	RSP 5%
CF34-8/10	CRJ700/900, EMBRAER170/190, ARJ21	Low-pressure turbine module, high pressure compressor rear stages, fan rotors, and gearboxes	RSP 30%
PW4000	A310/330/340, 777	Low-pressure turbine vanes, disk, combustor, and active clearance control	RSP 11% and subcontract
GE90	777	Low-pressure turbine rotor vane disks, and long shafts	RSP 10%
Trent700/800	A330, 777	Low-pressure turbine vanes, disks, long shafts, low-pressure turbine disks, and turbine cases	RSP 2.7 to 4%
V2500	A320, MD90	Fans, low-pressure compressors and fan cases	Program partner 23%

Required Surveillance Performance = A set of requirements for air traffic service provision, aircraft capability, and operations needed to support performance-based surveillance within a defined airspace.

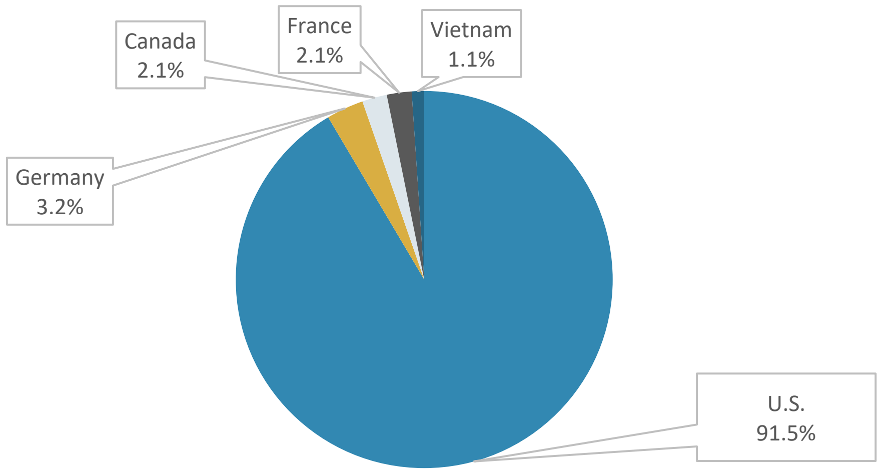
Source: Japanese Aerospace Industry 2020–2021

Japan is a leading trade partner with key aerospace manufacturing countries in North America and Europe. The U.S. is the leading trade partner of Japan for aircraft, spacecraft and parts, followed by Germany, France and Canada. The U.S. dominates the exports from Japan with a share of 86% while it also leads the imports to Japan with a share of 60%. With recovering economies and aerospace industries in North America and Europe along with evolving domestic production, the demand for aerostructures and components manufactured in Japan is estimated to grow during the forecast period, which will also drive the consumption of ceramics and composites in Japan during the forecast period.

Figure 48

Shares of Aircraft, Spacecraft and Parts thereof Exported from Japan, by Top Destinations, 2020

(%)

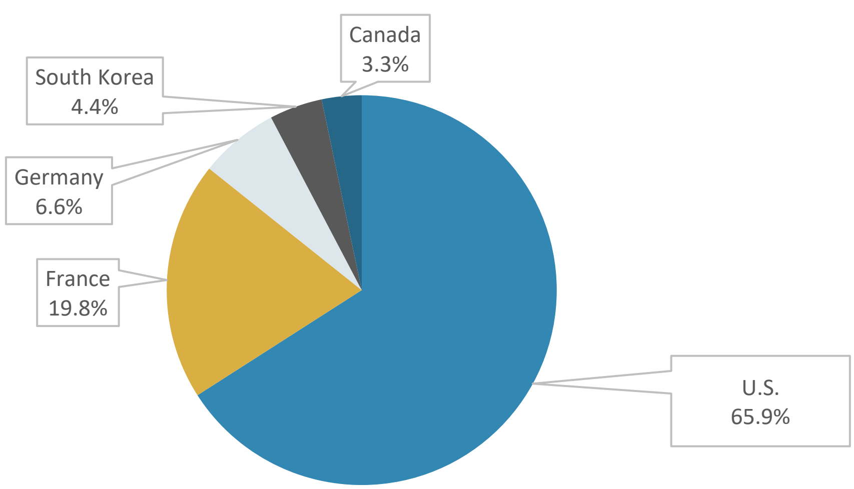


Source: ITA, HS code 88

Figure 49

Shares of Aircraft, Spacecraft and Parts thereof Imported into Japan, by Top Sourcing Countries, 2020

(%)



Source: ITA, HS code 88

South Korea

South Korea is another leading market for aerospace ceramics and composites; it supplies aerospace components for domestic and foreign markets. The industry had been rising for several years when it was hit by the effects of the COVID-19 pandemic. A drop of at least 30% is expected in the Korean aerospace industry in 2020.

Table 67
South Korea Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	54.4	56.6	77.1	6.4
Defense	39.6	41.5	83.2	14.9
Space	4.9	5.1	22.9	35.0
Total	98.9	103.2	183.2	12.2

Source: BCC Research

The industry is led by demand from the commercial segment followed by defense, with a combined share of 95%. The defense segment, in general, accounts for the largest share in the aerospace production industry in South Korea. However, after considering the maintenance, repair and operations (MRO) turnover, the commercial aerospace segment accounted for more than 50% in 2019.

The commercial aerospace segment turnover is comprised of production of components manufactured for Boeing and Airbus along with MRO. The defense segment refers to different production programs for different military jets and rotorcrafts. Korea aerospace suppliers have partnered with regional and foreign companies such as the Agency for Defense Development (ADD), Airbus, Boeing, and Lockheed Martin. Due to increasing defense expenditures and recovering air travel in APAC along with progressing domestic production of high-tech aircraft, it is anticipated the Korean aerospace industry will grow rapidly during the forecast period. These developments will help fuel the demand for ceramics and composites in the commercial and defense segment in near future.

The space segment registered 64% Y-O-Y growth during 2018–2019. The segment is expected to experience a steady growth due to satellite programs such as geostationary orbit complex satellite, mid-size satellite, and next generation satellite development, which is expected to drive the demand for ceramics and composites in the space segment during the forecast period.

Table 68
South Korean Aerospace Industry, 2016–2020
($ Millions)

	2016	2017	2018	2019	2020 (E)
Domestic supply	5,117	3,969	4,714	6,028	6,298
Imports	5,284	3,553	4,635	5,281	5,571
Total trade	10,401	7,522	9,349	11,309	11,869
Domestic demand	7,859	5,436	6,732	8,487	9,223
Exports	2,542	2,086	2,617	2,822	2,646

2020 (E)= Estimated values

Source: Korean Aerospace Industries Association

Table 69
Aerospace Programs and Shares of Production, 2019
(%)

Program	Segment	Share of 2019 Production (%)
T-50 Program	Defense	8.5
KT-1 Program	Defense	0.2
KUH Program	Defense	11.6
LAH/LCH Program	Defense	1.3
KF-X Program	Defense	8.3
F-15 Program	Defense	0.6
AH-64 program	Defense	0.9
Comm. Aircraft Parts	Commercial	28.6
MRO	Commercial	18.7
Engine Parts	Commercial	6.7
UAV	Defense	2.3
Space Program	Space	5.0
Others	–	7.2
Total		100

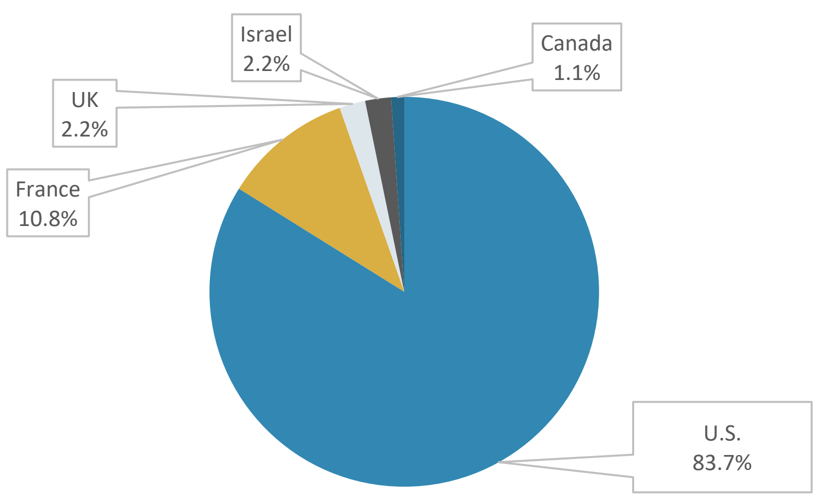
Source: Korea Aerospace Industry 2020–2021

Table 70
South Korean Aerospace Industry, Exports and Imports, 2017–2020
($ Millions)

Segment	2017		2018		2019		2020	
	Exports	Imports	Exports	Imports	Exports	Imports	Exports	Imports
Aircraft	814	1,295	630	2,155	449	2,810	476	2,963
Parts	2,305	2,079	2,317	2,263	2,421	2,268	2,567	2,392
Space Parts	31	180	208	217	20	203	21	214
Total	3,150	3,554	3,155	4,635	2,890	5,281	3,064	5,569

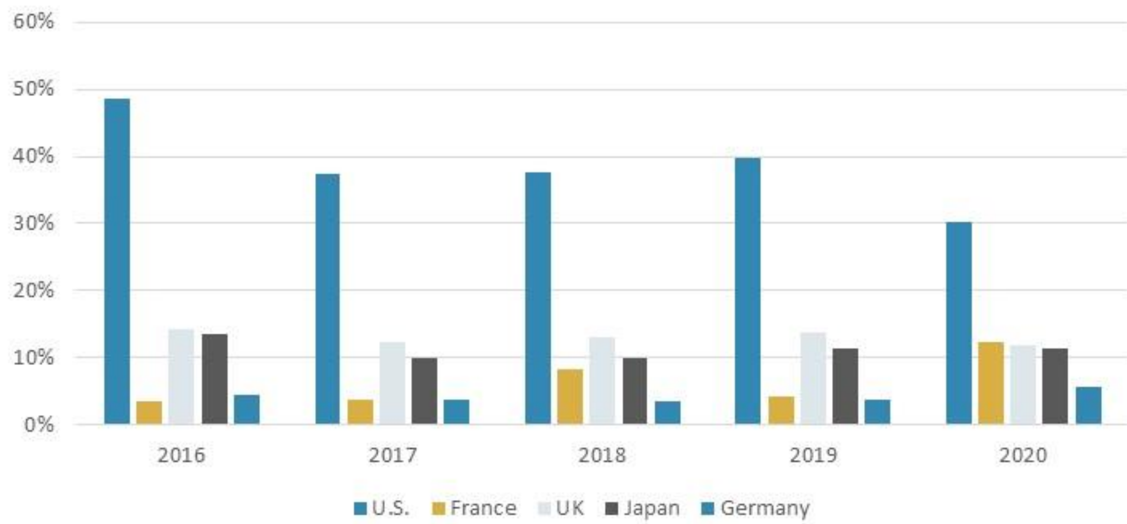
Source: Korea Aerospace Industry 2020–2021

Figure 50
Shares of Aircraft, Spacecraft and Parts Thereof Imported into South Korea, by Top Five Sourcing Countries, 2020
(%)



Source: ITC, HS code 88

Figure 51
Shares of Aircraft, Spacecrafts and Parts Thereof Exported from South Korea, by Top Five Destination Countries, 2016–2020
(%)



Source: ITC, HS code 88

Table 71
Key Companies in Korea Aerospace Composites Market

Company	Business Segment	Composite Products	Website
HIZE Aero Co. Ltd.	Composite Assembly/Metallic Assembly/Machining, Sheet Metal, Tooling, Special Process	B787 Fixed Trailing Edge, Center Wing Box; B767 Sec.48 AFT Body Tail Cone; B737 Horizontal Stabilizer Spar Chord, Airstair Door	www.hizeaero.com
C&LEE Inc.	Composites, Aluminum Heat Treatment	B777 Fixed Leading Edge: Inboard Panel, Outboard Panel; KUH: Door, Lower Panel, Cowling	www.candlee.co.kr
Dongsung TCS Co. Ltd.	Composite Parts	B737 FSF, B777 FSF/RWT/WBE, B787 FSF/RWT, A320 SL, A350 CD	www.dongsungtcs.com
DONGYOUNG M&T Co. Ltd.	Aircraft Parts, Composite Parts Process, Design of Aircraft Tool and Production, Special Material Cutting	Special Metal (Ti, Inconel, Composite etc.); Precision Configuration Cutting (water jet); Composite Part 5 Axis Precision Machining	www.dymnt.co.kr
Hankuk Carbon Co. Ltd.	Composites	Carbon Prepregs, LNG, Glass Papers, Composite Parts, Electronics, Dry Films	www.hcarbon.com
Hankuk Fiber Co. Ltd.	Composite Parts	Airbus A320 Elevator, UAV Structural Body and Part, KT-1 Windshield (KT-1 Canopy	www.hfiber.com

Company	Business Segment	Composite Products	Website
		Transparency), UH-60 Black Hawk Crew Seat, B747/757/767/777 Nose Cone, Air Inlet Duct, Engine Cowling, Fuel Vent Duct, Radome CW396	
KOLON DACC Composite Co. Ltd.	Composite Material	T/TA/FA-50 External Fuel Tanks; KT(O)-1 External Fuel Tank; KGGB Main Wing Assembly, Outlet Guide Vane	www.kolondacc.co.kr
Korea Composites Inc.	Aerospace, Military and Industrial Composite Parts (Structural, Interior)	B787 PBH, A350 NLGB, P-8A RWT, P-8A HS, B787 FTE Door, A-10 OWP/CWP, KGGB Skin, T-50 Nose Cone, A350 Business Class Back Shell	www.kci.so
Nexcoms Co. Ltd.	Composites and Systems Application	OPV (Optionally piloted vehicle), Hydrogen Fuel Cell UAV, Exhaust Nozzle, Blade, Bearing-less Hub, Electrical HALE (High Altitude Long Endurance) UAV, CFRP Ring Frame, Subfloor	www.nexcoms.com
Songwol Co. Ltd., Songwol Technology	Composite Parts	B787 FTE Metal bond, B777 FLE Metal bond, B737 HS Metal bond, B737 MAX Advanced Winglet, B737 NG/MAX Tip Cap Composite, B767 ATB RIB Assy Metal Bond, AH-64 Composite Laminate, T-50 Composite Engine Protection Screen, T-50 VS Composite Test Specimen, KT-1 Engine cowl assembly	www.songwoltech.com
TOPS Co. Ltd.	Waterjet System Solution	Waterjet Machining-Cutting (Spacers, ribs, blades);Roughing (Blisks, blades, leading edges); Drilling (Plugs, nacelle parts); Degating, Deflashing (Forges, blades, landing gear); Materials : Composites (CFRP, superalloys, titanium, aluminum, stainless steel); Waterjet Stripping for MRO (Parts, Coatings, Substrate)	www.topswaterjet.com

Source: Korea Aerospace Industry 2020-2021

Rest of APAC

The rest of APAC market is comprised primarily of India, Australia and Singapore. The aerospace industry in these countries is mostly made up of aircraft component manufacturing, MRO and assembly operations. The aerostructure and component manufacturing contributes a small share in the regional industry compared to other players such as China and Japan.

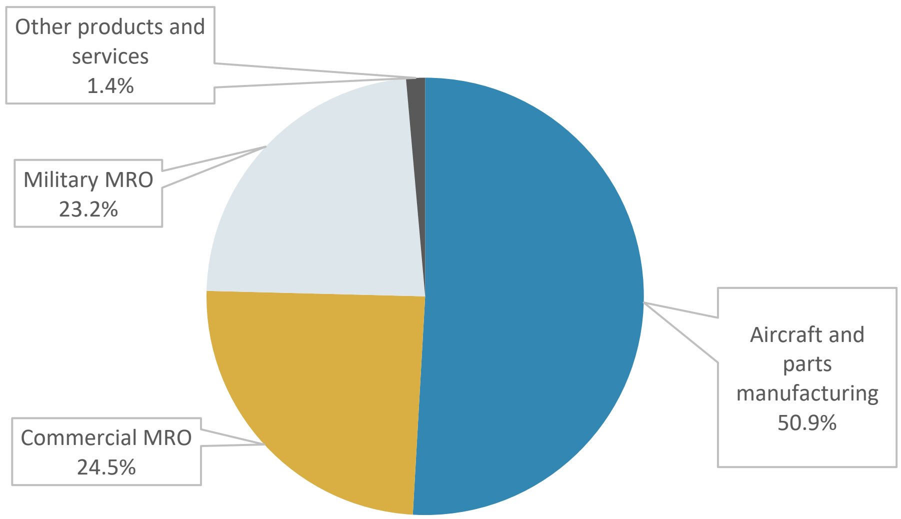
Table 72
Rest of APAC Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	38.1	39.7	60.5	8.8
Defense	20.3	21.4	47.2	17.1
Space	5.1	5.2	32.3	44.1
Total	63.5	66.3	140.0	16.1

Source: BCC Research

The Australian aerospace industry is made up primarily of Boeing Australia Holdings Pty Ltd., BAE Systems Australia Holdings Ltd. and Airbus Australia Pacific Ltd. These companies lead the composite parts manufacturing and MRO operations in the country. Boeing Aerostructures Australia manufactures composite aerostructures. The company manufactures ‘moveable trailing edge’ control surfaces for the 787 made of carbon fiber with resin infusion. Some other components manufactured here are 737 ailerons, 747 moveable leading edges, along with 777 cove lip doors, elevators and rudders. A larger share of the country’s aircraft manufacturing is comprised of helicopters and light aircraft used for recreational, agricultural and training purposes.

Figure 52
Shares of Australia Aerospace Manufacturing Industry, by Segment, 2017–2018 (%)



Source: KPMG Australia's Aerospace Industry Capability, 2019

India has promise as a lucrative potential market for aerospace manufacturing companies considering the growing air travel and defense budget of the country. Currently, commercial aircraft demand is met by imports from developed regions. Domestic production is led by military rotorcraft and jets, followed by commercial and space parts. Most of the aircraft and component production is done by joint ventures between domestic manufacturers and foreign companies.

The government has been instrumental in making domestic aerospace production more attractive through supportive policies and subsidiaries. Some of the key programs run by government are "Make In India" and ''Atmanirbhar Bharat," which focus on boosting the manufacturing industry in the country. The first program promotes production of aircrafts and components in the country through collaboration with companies from foreign countries. The latter program is intended to encourage local companies to explore the aerospace manufacturing industry. Companies such as Hindustan Aeronautics Ltd (HAL) and Mahindra & Mahindra has manufactured business jets and play an important role in local production of military aircrafts.

The key drivers for the Indian aerospace industry are the growing disposable income of the middle class, recovery from the economic effects of COVID and an increasing defense budget. With increasing demand from the regional air travel and defense industry, it is anticipated the aerospace manufacturing industry will attract more investments in India, a factor that will increase demand for ceramics and composites during the forecast period.

Some of the leading aerospace composite companies in India are Tata Group, HAL, Kineco Kaman Composites, Valeth High Tech Composites, Taneja Aerospace and Aviation Ltd., and Adani Defense and Aerospace Group.

Singapore is a leading manufacturer of aerostructures and components. The country plays a significant role in the global MRO industry, accounting for around a 10% share in the industry. The aerospace industry is characterized by the presence of all leading aircraft and engine manufacturers in the country. The production and MRO operations of these companies drive the demand for ceramics and composites in the country.

Some of the key players in the aerospace composites industry in Singapore are ST Engineering Land Systems Ltd., Universal Aviation Industries PTE Ltd. and Voestalpine Specialty Metals PTE Ltd.

Table 73
Aerospace Industry in Singapore, 2017–2020
($ Millions)

Metric	2017	2018	2019	2020 (Estimate)
Local production	7,004	7,606	8,140	6,675
Exports	10,112	13,553	16,249	12,531
Imports	14,864	22,172	25,153	19,131
Imports from the U.S.	8,357	13,193	14,775	10,692
Total market size	11,756	16,225	17,044	13,275

Source: International Trade Administration

The following table lists the key players in Singapore’s aerospace industry. These companies primarily serve the manufacturing and MRO segments of the industry.

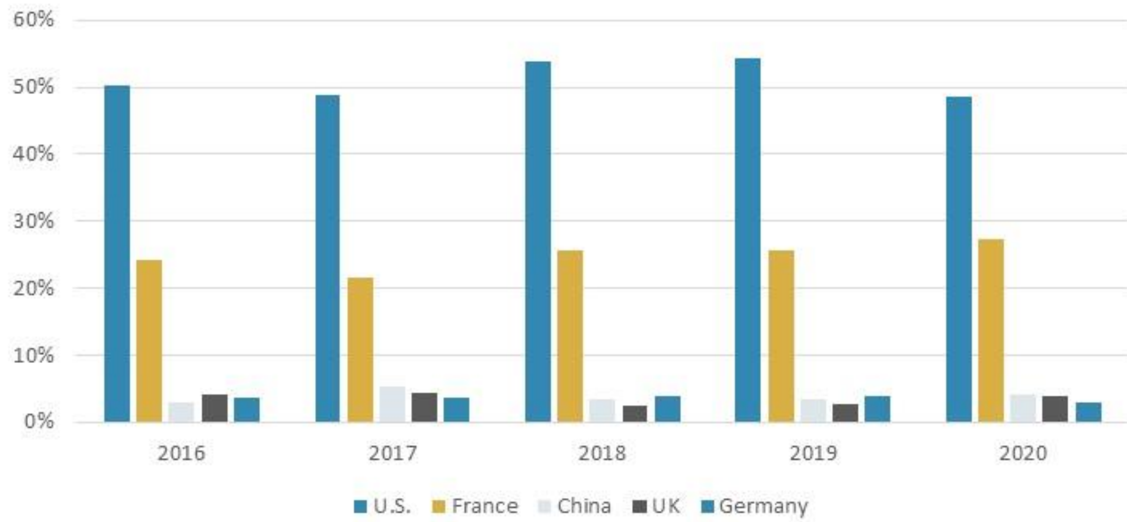
Table 74
Key Players in the Singapore Aerospace Industry

Manufacturing	
Company	Description
Collins Aerospace	Collins' Singapore facility houses its global Centre of Excellence for gear manufacturing, and manufactures components for electric power generation, air management systems and engine controls.
GE Aviation	GE Aviation manufactures aircraft engine components for the high-pressure compressor section of the GE9X engine at the Seletar Aerospace Park.
Rolls-Royce	Rolls-Royce assembles and tests its Trent 1000 and 7000 aero engines in Singapore. The facility is also the first of its kind outside of the U.K. to manufacture the titanium Wide Chord Fan Blade.
Additive Flight Solutions	This is a joint venture between SIAEC and Stratasys. It is a service bureau providing design, engineering, production, and certification support for additive manufactured aerospace components.
Pratt & Whitney	Its Singapore manufacturing facility is one of two Pratt & Whitney global sites manufacturing hybrid metallic fan blades for the geared turbofan (GTF) family of engines.
Thales	The avionics production facility in Singapore manufactures key systems for the A320, A350 and B787 fleets, including flight control computers, displays and electrical systems.
MRO	
Company	Description
Singapore Component Solutions	This is a joint venture of AFI KLM E&M and Sabena Technics. The company supports A320 and ATR component repairs in Singapore.
Bombardier	Bombardier's Singapore Service Centre provides maintenance, refurbishment and modification services to customers, and is introducing an aircraft painting facility and will more than double the size of its integrated parts depot.
Collins Aerospace	Collins' Singapore facilities provide MRO services for actuation systems, interiors, composite nacelle systems, engine control, electrical power systems, sensors and integrated systems, engine components, and other aerostructures.
GE Aviation	GE Aviation's Centre of Excellence for combustor and airfoil component repairs in Singapore repairs a wide range of components for GE and CFM commercial engines.
Meggitt	Meggitt provides a range of spares distribution and MRO services for components including heat exchangers, valves, sensors, fires and safety equipment, as well as wheels and brakes.
Moog and SIAEC	Moog Aircraft Services Asia, a joint venture with SIAEC, provides flight control actuation component MRO services for the Boeing 787 and Airbus A350.
ST Engineering	Expanding capabilities to include A350 for airframe MRO as well as engine MRO for CFM LEAP-18 Quick Turn.
Pratt & Whitney	Eagle Services Asia, a joint venture between Pratt & Whitney and SIAEC, carries out MRO for various engine families including the PW 4000, GP7200 and new GTF PW1100G-JM engine.

Source: EDB Singapore Aerospace Industry

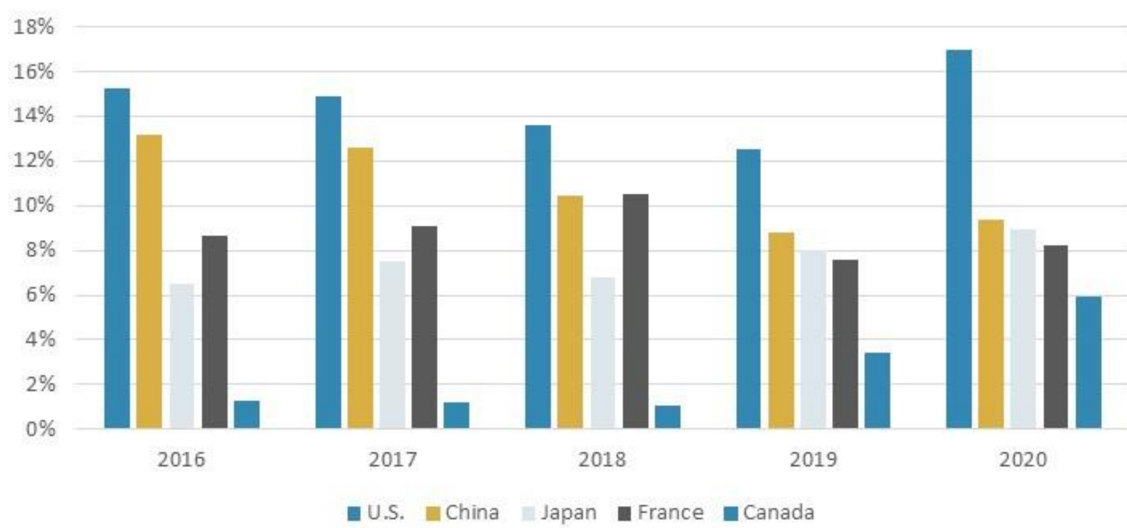
Singapore also plays an important role in international trade of aircraft and components. The U.S. contributes the largest share of both imports into and exports from the country.

Figure 53
Top Five Sources of Aircraft, Spacecraft and Parts thereof Imported into Singapore, 2016–2020



Source: ITA, HS Code 88

Figure 54
Top Five Destinations of Aircraft, Spacecraft and Parts thereof Exported from Singapore, 2016–2020



Source: ITA, HS Code 88

Rest of the World

The Rest of the World market is made up of the Middle East and Africa and South America. In the Middle East and Africa, the aerospace manufacturing industry is led by United Arab Emirates (UAE) and Israel. The South American aerospace industry is led by Brazil, due to presence of Embraer S.A. in the country.

Table 75
Rest of the World Market for Aerospace Ceramics, by Subregion, Through 2026
($ Millions)

Subregion	2020	2021	2026	CAGR% 2021–2026
Middle East and Africa	197.8	201.7	363.5	12.5
South America	131.8	137.8	240.8	11.8
Total	329.6	339.5	604.3	12.2

Source: BCC Research

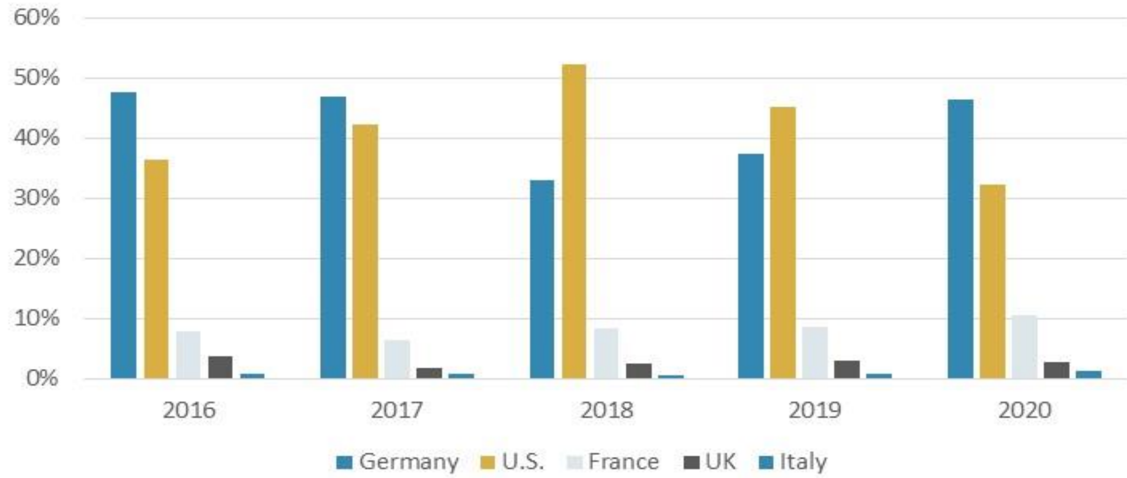
Table 76
Rest of the World Market for Aerospace Ceramics, by Segment, Through 2026
($ Millions)

Segment	2020	2021	2026	CAGR% 2021–2026
Commercial	197.8	203.7	272.6	6.0
Defense	98.9	101.8	179.5	12.0
Space	32.9	33.9	152.2	35.0
Total	329.6	339.4	604.3	12.2

Source: BCC Research

The aerospace industry in UAE is located in a five-square kilometer facility called the Nibras Al Ain. This facility hosts aerospace manufacturing and service providers such as Strata, AMMAROC, EDIC Horizon, and ADASI. Strata Manufacturing PJSC (STRATA) is the only manufacturer of composite-based aerostructures in the region. The client base for STRATA is comprised of leading companies from the commercial as well as military aerospace segments including Airbus, Boeing, Leonardo S.p.A, Pilatus, SAAB, and SABCA. The UAE government has ambitious plans to build a city on Mars by 2117. For this plan the space agency of the country is focusing on in-house production of spacecraft. The UAE Space Agency has managed to successfully to send an orbiter to Mars with the assistance of U.S. universities and companies. The country has entered into collaborations with U.S., Japan, and China, U.K., Italy, and Russia for space exploration missions.

Figure 55
Top Five Sources of Aircraft, Spacecraft and Parts thereof Imported into UAE, 2016–2020



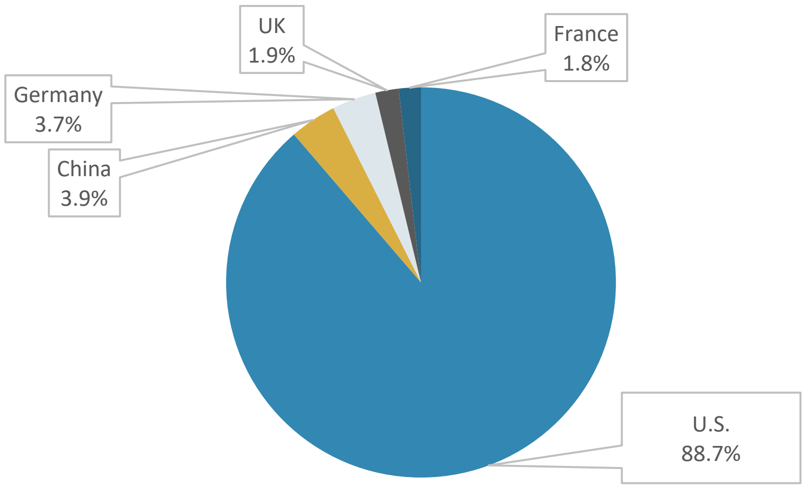
Source: ITC, HS Code 88

Another key market for ceramics and composites in the aerospace industry in the Middle East and Africa is Israel. The country is known for its military aerospace industry, especially UAVs. Israel is a global leader in UAV production and exports along with independent space launching capabilities. The UAV industry is characterized by low-cost production, high-end technologies and top-quality products. The key players in the UAV market are Israel Aircraft Industries (IAI), Elbit Aeronautics, Rafael, Urban Aeronautics, UVision Air, and BlueBird Aero Systems.

The local aerospace manufacturing industry capabilities also include machining, electronic systems, components, and composite materials. Israeli companies work with leading players in the global aerospace segment including GE, General Dynamics, Embraer, Boeing, BAE Systems, Pratt & Whitney, Northrop Grumman, Lockheed Martin, and Raytheon. The country plays an important role in the ceramics and composites market due to domestic commercial and defense aerostructure production. Some of the aerostructures manufactured in Israel are for the F-35, F-15, F-16, Boeing 777/777X/787, T-38, and helicopter structures.

Israel is considered a pioneer when it comes to technical expertise for small satellite development technologies. The Israel's space agency collaborates with leading space agencies from developed regions such as NASA and ESA, leveraging each other's expertise and capabilities.

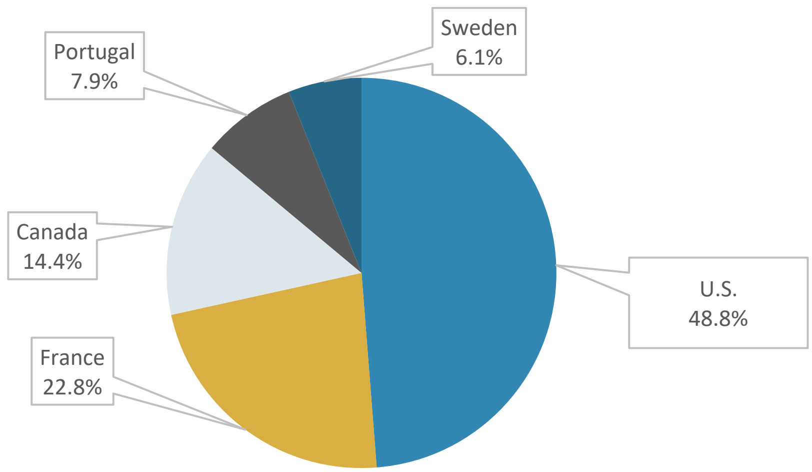
Figure 56
Top Five Sources of Aircraft, Spacecraft and Parts Thereof Imported into Israel, 2020



Source: ITC, HS code 88

The South America aerospace industry is led by Brazil due to the presence of Embraer, a leading regional aircraft manufacturer. The Brazilian aerospace industry provides turboprops, military aircraft, agricultural aircraft, business aircraft, and helicopters. The industry mostly imports components and parts from the U.S. and exports assembled aircraft.

Figure 57
Shares of Top Five Sources of Aircraft, Spacecraft and Parts Thereof Imported into Brazil, 2020



Source: ITC, HS Code 88

Chapter 8

Emerging Materials: Background and Applications

Chapter 8: Emerging Materials: Background and Applications

Aerospace materials include many categories of advanced materials that offer improved performance, lighter weight, higher strength, improved safety, and in some cases lower cost than conventional technologies. Even though material costs may be higher, many ceramic-based and other newer aerospace materials can more than offset their high initial cost through reduced operational cost, reduced fuel usage, and reduced maintenance and repair cost.

This chapter provides a background discussion on aerospace materials and their applications to offer readers a clear understanding of the types and categories of aerospace materials. Aerospace materials serve as versatile alternatives to conventional materials and this chapter reviews such overlaps in terms of recent historic perspective as well as anticipated future development. This chapter also summarizes key performance metrics for aerospace materials and reviews recent development in the industry.

Background

Rising demand for improved fuel efficiency, enhanced performance and increased safety is driving the aerospace industry to deploy new, lighter weight, stronger materials that were once considered too costly or too difficult to utilize for day-to-day production activities. Historically, the aerospace materials market transitioned away from aluminum towards carbon fiber-based composites and honeycomb structures, while maintaining use of superalloys and other physically heavy materials for critical parts such as engine/turbine components. Now, manufacturers increasingly rely on carbon fiber reinforced polymers (CFRPs) wherever possible. At the same time the industry has begun to view heavy working components of the airplane with increased scrutiny, looking to develop and deploy physically lighter materials and alloys. The key target for such alloys includes materials that are both lighter and also offer greater temperature resistance, where both properties can contribute to improved fuel efficiency.

Advanced materials are particularly important in current engine designs. Today's learn-burn engines carry temperature potentials of up to about 3800°F. Therefore, these high-efficiency systems also burn extra hot, potentially surpassing the melting point of currently available superalloys which is below 3500°F. Superalloys are still a mainstay in the engine/turbine production industry, but their weight and limited thermal properties leave the engine production industry ripe for transition to a new class of heat-resistant, lighter weight materials. Newer material classes include heat-resistant superalloys and non-metal composites including ceramics.

Finally, the space industry is growing in terms of market size. Over 80 countries now have satellites in space and private companies such as SpaceX and Boeing are increasingly making headlines as commercial players enter the marketplace. Market volumes for space industry specialty materials are still small and will likely remain so for the next five years. As a result, these are not considered in this report. However, overlap for materials in the commercial aircraft industry is significant, as many of the same materials have also been adopted for space-related activities and equipment. We will quantify these markets as one element of the approximately $250 billion space market.

History

Early aerospace materials focused on using the lightest metals available for airplane and rocket construction. Tt was the U.S.'s ability to quickly refine and separate large amounts of aluminum that helped the country manufacture airplanes rapidly during World War II. But perhaps the most significant early application for advanced aerospace materials in the industry centered on the construction of new types of engines. Engines subject to extreme heat and mechanical forces required the development of new metals and new alloys capable of withstanding extreme environments.

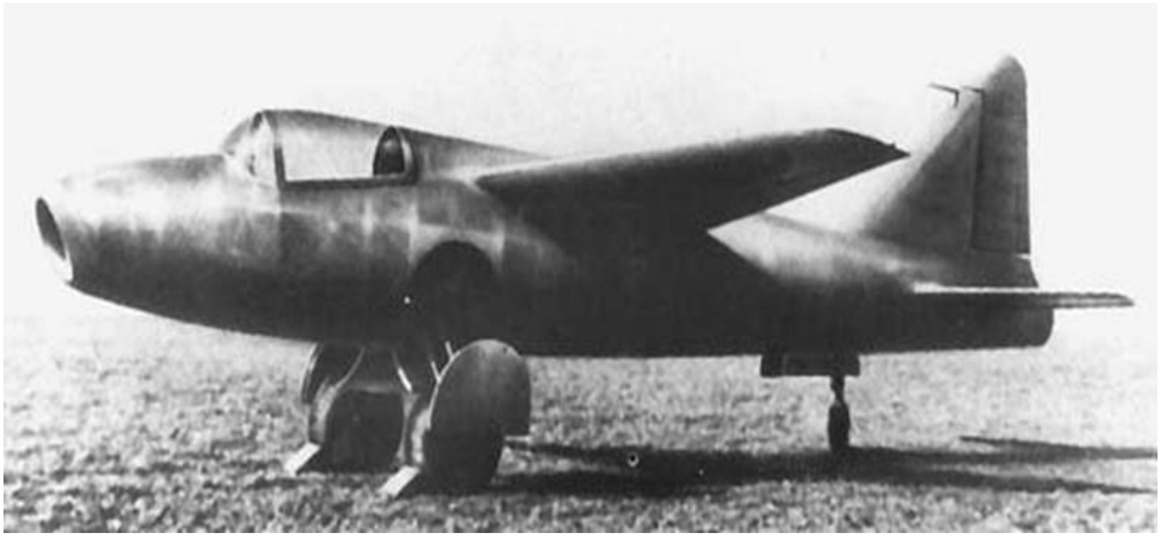
In the period of 1900 to1910, the reliability of steel was greatly improved by a process called vacuum melting. This process enabled manufacturers to have closer control of elemental compositions, and also prevented the unintended incorporation of airborne nitrogen and oxygen into the still as it formed. These gases could become physically trapped in the metals, reducing their strength. Vacuum melting was also a critical process in enabling the addition and control of various refractory and other specialty elements such as aluminum, tantalum and niobium. It also allowed careful control of the alloy production process and enabled manufacturers to tune the composition of nickel, cobalt, chrome, molybdenum, aluminum, and other elements without nonmetallic impurities.

Superalloys constituted the industry's first major new material-oriented advancement. The term "superalloy" came about in the mid-1940s to describe a group of recently invented alloys that could be used at exceptionally high temperatures, but that also maintain their strength, resistance and toughness at these high temperatures. These alloys were developed primarily in support of aircraft turbine engine development, which requires high performance under conditions of exceptionally high temperatures and high mechanical stress. These alloys maintained their strength almost wholly until they reached their melting points.

The need for temperature-resistant metals or steel was strongly driven by advances during the late industrial revolution and its outgrowth of various products. Initially nickel, chromium and cobalt were added to iron and were considered high-temperatures alloys into the 1940s. Engineers, particularly those were in U.S and Europe, invented an array of high-temperature alloys that were used to meet existing and perceived future industrial needs. However, in order to transition from high-temperature alloys to superalloys a new production technology was necessary.

Prior to the 1940s superalloys and their precursors found application primary in the manufacturing industry. Businessmen such as Elwood Haynes, an early automotive entrepreneur, sought to streamline, economize and speed up the automobile manufacturing process. This drive led to increasingly rapid machining, which ultimately was limited by cutting tools that would wear down rapidly, requiring frequent replacement. Demand surged for alloys that were able to withstand high temperatures while retaining their hardness. The solution came about as a cobalt-chrome alloy, which eventually evolved into vitallium (65% cobalt, 30% chromium, 5% molybdenum, and traces of other substances). Other new and highly resistance alloys being developed at that time included nickel-chromium alloys, cobalt-chromium alloys and iron-chromium-nickel alloys. These alloys targeted a range of applications including cutting tools for machines, alloys used for heating elements, internal combustion engine parts, steam turbine blades, pistons, and use in valves and valve components.

Figure 58
First Turbo Jet-Powered Aircraft, First Flight, August 1939



Source: MIT (2017)

By the 1940s and 1950s new airplane engine technology in the form of turbine engines became the principal driver for the development of superalloys and the superalloy production industry. As demand grew for increasingly durable alloys in the aircraft industry, high temperature and other early superalloy precursor metals gave way to the more common use of nickel- and cobalt-based superalloys. In this manner, gas turbine engine development and non-propeller engines in the aviation industry were founded on the heat resistant backbone of superalloys. Over the ensuing decades, superalloys found other applications, but the aircraft (and later the aerospace) industry remained the primary driver of the R&D and innovation encompassing the advancement of superalloys.

In 1950 and 1951, the re-emergence of vacuum melting for superalloy production led to another round of substantial progress in superalloy development. At this time the significant benefits of vacuum melting were more wholly recognized. These advantages included the minimization of oxidation and potential for oxygen removal from the existing composition of the metal prior to its melting. Vacuum melting and degassing techniques permitted the use of highly active elemental additions such as titanium. At this time titanium- and aluminum-containing alloys for jet engines rapidly transitioned from air melting to vacuum melting production techniques, giving the alloys new and enhanced creep strength and consistency never before realized.

By 1957, Allvac Metals co. opened its doors with the groundbreaking for installation of a 500 lb. vacuum induction melting furnace. With the first official melt in 1957, the company unexpectedly pivoted from military to commercial jet applications, chasing the market trends of the day. By the early 1960s the superalloy market was beginning to take off of and vacuum induction melting became the standard process for producing high-temperature alloys. From that time through the present, the commercial aerospace industry has remained the primary global market for superalloys. Subsequent years brought development and entrenching of industry favorite superalloys (for example alloy 718) along with alloy specifications and an increasing degree of standardization in manufacturing processes. Today superalloys are available in several product forms including.

- Ingots and billet for extrusions and die forgings.
- Slabs for rolling into plates and sheets.
- Billets and bars forged round or rectangular.
- Forged cylindrical or tapered and stepped shafts.
- Bar and coil shaped in round or rectangular forms.
- Hot rolled plate.
- Hot rolled sheet.
- Hot extruded tubing.
- Cold pilger rolling.
- Cold drawn bar, rod, coil, and wire.
- Cold rolled sheet and strip.

Aerospace materials have expanded into several additional key areas. These changes have come about from a continued demand for increased performance, reduced weight and strength with less bulk. Like the global automotive industry, the global aerospace industry is now undergoing a new round of significant material- and design-oriented upgrades focused largely on weight reduction. Reducing the weight of aerospace materials significantly reduces the amount of fuel needed to support operations. Over the last 20 years, this fact has become increasingly important not only to reduce the amount of money spent on fuel purchase, but also to reduce greenhouse gas (GHG) emissions, which has become critical to many countries. As a result, new advanced composites, ceramic-based composites and advanced alloys were given the opportunity to develop and expand into the market

Aerospace Materials

Advanced Steel Alloys

Conventional steels include carbon steel and steel plate. However, advanced steel alloys, particularly those that provide high strength or that are highly resistant to wear or corrosion, find frequent application in the global aerospace industry. Critical advantages of high-performance steel alloys can be difficult to reproduce using other materials. For example, high-strength carburizing steel can offer exceptional hardness, good fracture resistance, high fatigue strength, excellent corrosion resistance, and high temperature resistance all in a single alloy.

The primary drawback of steel is its weight. High-strength steel does, however, help to manage weight to some degree. For example, high-strength steel alloys are stronger than conventional steel and therefore require less mass/material. This reduced mass translates into reduced weight typically on the order of 10% in terms of weight reduction.

Common applications include structural elements, gears, helicopter and propeller transmissions and drivetrain elements, rotor shafts, fasteners, other highly loaded components, landing gear hook shank components, landing gears, actuators, munitions, gun barrels, blast resistant applications and impact containment.

Advanced steel alloys represent a new and continually refreshed set of materials that have a long history of development and improvement. Today's alloys continue to focus on improved performance, increased corrosion resistance, improved strength, and where possible weight reduction.

Advanced Aluminum Alloys

In comparison to neat aluminum, advanced aluminum alloy is largely focused on increasing strength. Alloying elements may not necessarily reduce material density, but can substantially increase strength, resilience and other key properties. Therefore, similar to high-strength steel, advanced aluminum alloys reduce the total amount of material needed. This in turn reduces weight overall, even though an advanced alloy might actually have higher density.

Aluminum alloys are commonly used in place of steel for structural elements in the aerospace industry. Today's aluminum alloys are high strength and can be highly resistant alloys that are actively designed to serve as an upgrade from older, less advanced aluminum alloys such as 7050-T74 aluminum alloy. Even 7000 series aluminum alloys, however, are considered exceptionally usable for a wide array of aerospace applications and are generally used as a replacement for lower grade aluminum alloy or where appropriate structural steel.

Common applications for advanced aluminum alloys include aircraft structural frame components, wingspans, internal components, and in some cases gearbox or drivetrain components. Engineers are continuing to push the limits of aluminum alloys as they look for new ways to reduce weight of key components. This process is increasingly pushing into moving components of aerospace equipment including airplanes and helicopters, where possible components are being redesigned and in some cases rethought entirely to accommodate lighter weight aluminum alloy material.

Titanium and Its Alloys

Titanium alloys provide exceptional lightness and strength. They are also more expensive than many of the more common steel and aluminum alloys. Key advances in titanium alloys are focused on how to incorporate lower-cost raw materials and thereby reduce the cost of the alloys overall. Other key benefits can include improved ductility and improved castability.

Titanium that is commercially pure titanium is also used in aircraft, its primary benefit being that its density is only 60% that of conventional steel while also exhibiting high strength and excellent corrosion resistance. Titanium also exhibits good compatibility with CFPR including corrosiveness and thermal expansion rates. Titanium alloys further improve on these benefits. In fact, the amount of titanium used in fuel efficient aircraft has been growing significantly. In fuel efficient aircraft, for example, the amount of titanium used can be two or three times that of a conventional aircraft. From 2010 through early 2020, available data indicate that the demand for titanium and its alloys for aerostructure materials nearly quadrupled.

Titanium and its alloys are increasingly being considered for airframe structural components. In frames and joints where high-strength steel was once required titanium alloys are now frequently used to save weight. Titanium is also being incorporated into select elements of turbofan engines. While superalloys of steel are required in the combustion and turbine sections of jet engines, titanium alloys are increasingly used in the cooler compressor sections, which feed the combustion and turbine segments. Newer uses for titanium and its alloys include reinforcement for airframe structure conversions, support for cargo loading platforms and conveyor systems, and installation of oversize doors and hatches.

Titanium alloys in the aerospace industry may include roll formed stringers, extrusions, sit track to sheet, plate, bar and tubing elements. These are common structural elements for airframes as well as steel sections, bulk heads and other plane segments. New titanium alloys that provide increased casting performance and further ductility improvements could result in more widespread adoption of these alloys across an increasing scope of aerospace platforms, where titanium corrosion resistance and strength could potentially combine reduced cost with near net shape processing.

Superalloys

There are three basic categories of superalloys: nickel, iron and cobalt-based superalloys.

Nickel Superalloys

Nickel-based superalloys are best suited for power generation and air jet turbine applications, with primary solutes in the nickel matrix being chromium, aluminum and titanium. Nickel superalloys are the most common in terms of production volumes and applications, relying on nickel as a primary base metal.

Nickel superalloys find wide use in load bearing structures, especially within the combustion section of gas turbine engines. They provide the highest homologous temperature of common alloy systems, retaining their strength at up to 90% of their melting point. The combination of a nickel base metal with up to about 10% (or sometimes 20% or more) of aluminum, chromium and titanium generates a two-phase equilibrium microstructure. These consist of gamma and gamma prime microstructures, which are largely responsible for the elevated temperature strength and other keystone properties exhibited by superalloys.

Iron Superalloys

Iron-based superalloys are generally considered to be of a lower grade than nickel or cobalt-based superalloys. However, iron superalloys are also less costly to produce. Iron-based superalloys are classified by the American Iron and Steel Institute (AISTI as follows:

- AISI 601 through 604: Martensitic low-alloy steels.
- AISI 610 through 613: Martensitic secondary hardening steels.
- AISI 614 through 619: Martensitic chromium steels.
- AISI 630 through 635: Semi-austenitic and martensitic precipitation-hardening stainless steels.
- AISI 650 through 653: Austenitic steels strengthened by hot/cold work.
- AISI 660 through 665: Austenitic superalloys: all grades except alloy 661 are strengthened by second-phase precipitation.

Like other superalloys, iron-based superalloys are generally characterized by strength and resistance to creep, corrosion resistance, oxidation resistance, and wear resistance at high temperature. Iron-based superalloys also exhibit these properties under room-temperature conditions. Wear resistance is a particular strength of iron-based superalloys, particularly when increasing levels of carbon are incorporated, which acts to enhance this property. Resistance to oxidation can also be enhanced with increasing chromium content.

Iron-based superalloys are available in all conventional mill forms, including billet, bar, sheet, and various forgings. Special shapes are also readily available for most iron-based superalloys. In general, austenitic (containing chromium and nickel, as well as sometimes molybdenum and nitrogen) alloys are more difficult to machine than martensitic (typically at least 12% chromium, and up to about 1.2% carbon content) types, which machine best in the annealed condition. Austenitic alloys are usually best when machined after being partially aged or fully hardened.

Cobalt Superalloys

Cobalt-based superalloys derive from a series of stellite alloys that were originally patented in the early 1900s by Elwood Haynes. Today, cast and wrought cobalt-based superalloys continue to be used because they can be engineered to have higher melting points than nickel or iron-based superalloys. This property can enable them to absorb stress under a higher absolute temperature.

Due to high chromium content in many cobalt-based superalloys, they can support increased corrosion resistance, even in high-performance gas turbines.

Many cobalt alloys provide enhanced resistance to thermal fatigue as well as and enhanced weldability in comparison to nickel-based superalloys.

Like nickel-based superalloys, cobalt-based superalloys also carry a face-centered cubic structure, when stabilized (such as at room temperature). Precipitation of carbides can harden cobalt superalloys, and they therefore typically contain carbon as an additive. Chromium is frequently added to enhance corrosion resistance, while various other metals may be added to enhance other specific properties. Other metals such as tungsten, molybdenum, tantalum, niobium, zirconium, and hafnium can be added to provide solid solution strengthening.

In comparison to nickel-based superalloys, the stress rupture curve for cobalt alloys is flatter and shows lower strength to about 930°C. The greater stability of carbides, which provide strengthening of cobalt alloys, then asserts itself. This factor is the primary reason cobalt alloys are used in the lower-stress, higher-temperature stationary vanes for gas turbines.

Composite Materials: CFRPs

Carbon fiber-reinforced polymers (CFRPS) offer many significant benefits for the aerospace industry. CFRPs are both strong and lightweight. They can be used for the manufacture of various aerospace materials and equipment, and they are already being used in many of the products used in people's daily lives, from bicycles to automobiles.

Within the CFRP matrix, it is the carbon fibers themselves that provide strength to CFRP systems. Carbon fiber mesh or fabric is then set within a thermosetting resin, which may be an epoxy, vinyl ester or polyester polymer.

In addition to standard CFRPs, this category also includes carbon fiber-reinforced thermoplastic composites. These materials are structurally similar to standard CFRPs, except that they provide increased heat resistance, thanks to a reliance on a thermoplastic base for the thermosetting resin. As a result, these materials can withstand higher operating temperatures than standard CFRPs, including those that rely on thermoplastics, and offer the following beneficial properties:

High Strength-to-Weight Ratio

Carbon fiber composites are typically much stronger than conventional metals and alloys, on a weight basis. For example, CFRP is typically about five times stronger than an equivalent mass of structural steel. As a result, significantly less mass is required to provide the same structural support as a conventional steel frame. Another example is that CFRP is approximately 1.5 times stronger than aluminum on a mass basis.

Lightweight

Lightweighting is a key consideration for the aerospace industry, and CFRP typically holds a density of only about 0.055 lbs. per cubic inch. In contrast, conventional fiberglass reinforced plastic carries a density of about 0.065 lbs. per cubic inch, while aluminum ranks at 0.098 and steel ranks at 0.29.

CFRPs also suffer from drawbacks. First, they are very high cost. In comparison to conventional fiberglass, CFRP costs at least five times as much, on a weight basis, and up to 20 times as much. In comparison to steel and aluminum, costs can be 20 times as much, 30 times as much or even higher. Cost is a significant consideration for when and how to use CFRPs in the global aerospace industry.

CFRPs also conduct electricity, like a metal, but do not conduct heat as well as metals. Conducting heat is perhaps more of a consideration for the aerospace industry, a fact that limits the use of CFRP or requires re-engineering of mechanical parts for many potential mechanical applications.

Advanced Composites

Typically we think of composite materials as including a combination of glass or carbon fiber substrate with a polymer-based matrix material, as is used in CFRP or fiberglass. However, the strict definition of a composite material is simply that it contains at least two parts: a reinforcement element, which works by providing structural and mechanical strength, and the matrix material, where the matrix material simply holds the structural elements together and in place. There are many types of materials that can be used as composites.

One such category of advanced composites is ceramic matrix composites (CMCs), which are a specific category of composites that rely on ceramics for both structural and matrix elements. Other secondary fibers can also be incorporated into the matrix, to provide additional improvements and desired properties. Reinforcing fibers can range in diameter from roughly that of a hair down to exceptionally small nanofibers. These are typically woven into a fabric or fiber system. Key advantages of CMCs include:

- High mechanical strength even at exceptionally high temperatures.
- Stiffness
- Mechanical stability.
- Thermal stability.
- Dimensional stability.
- Chemical resistance.
- Corrosion resistance.
- Fracture resistance.
- Ultra-lightweight.
- High durability.

CMCs do not, however, exhibit high compressive strength, and delamination can be a concern in some cases.

The primary driver behind the development of advanced composites is the need to maintain operability even under extremely high temperatures, up to 1800° C or higher. Applications for these advanced composites include high stress/high-temperature operations. These can include turbine blades, stator vanes, bulletproof armor heating elements, heat exchangers, burner parts, refractory elements, jet engine thrust control flaps, insolation, heat shields, burner stabilizers, rocker propulsion equipment, thermo photovoltaic burners, jet engine/turbo components, and combustion liners/refractory elements for gas turbine engines.

Advanced Adhesives

Advanced adhesives for aerospace applications include several categories of aerospace tapes and adhesives. Common tape products Include polyurethane protective tape and structural adhesive film. Other advanced adhesives used in the aerospace industry include urethane adhesive, epoxy adhesives, specific bonding adhesives for, for example, brackets, structural adhesives, and structural adhesive films.

Historically, aerospace adhesives have been used as a means to bond insulation, internal panels and flight control surfaces. These uses continue today, for example in bonding face skins to honeycomb core in sandwich constructions. However, across the industry, we are continuing to see growing applications and opportunities for the use of advanced adhesives in composite primary and secondary structural elements and associated assemblies

Adhesive properties can be tailored to specific uses. The results can include substantial changes in their overall properties and function. For example, advanced adhesive formulation can target changes in viscosity, cure time, toughness, heat resistance, chemical resistance, and other properties.

A small percentage of advanced adhesives can be considered structural for use in the aerospace industry. To meet industry standards, such a material must be able to maintain its strength under a shear force of 1.000 psi, when tested according to standard industry practices. These adhesives are commonly available as a paste or as an adhesive film or sheet. Pastes can be used to fill bridge gaps, and can also be deployed to bond parts together In contrast, adhesive films are used in large areas to provide structural bonding, and usually focus more extensively on bonding composites rather than metals. Some adhesives work by forming covalent bonds between surfaces which further enhances their bond strength, and ultimately results in a more effective bonding environment.

Applications

The following applications for aerospace materials are considered in this chapter: commercial passenger and commercial transport aircraft, general aviation, helicopters, defense industry and government, and the commercial space industry.

Commercial Passenger Aircraft and Commercial Transport Aircraft

These two categories are treated separately in the market sections but are combined here because the types of advanced aerospace materials used in both categories are similar, and the planes themselves are also similar in outer body construction and engine/propulsion systems. There are two main facets to commercial aircraft: commercial passenger aircraft and commercial transport aircraft. The most successful commercial passenger aircraft globally include the Boeing 737 class, followed by the Airbus A320 aircraft. During 2019 and early 2020, approximately 50 to 60 of each of these aircraft were being manufactured every month. These are medium- to short-haul jets that can hold approximately 120 to 240 passengers. Demand for the jets has grown in recent years thanks to airlines increasing focus on more direct flights, and fewer centralized transfers. This trend has resulted in demand for small- to mid-sized planes that are capable of meeting regional demand at mid-sized airports, while avoiding excess capacity.

Boeing and Airbus are not the only players in the commercial aircraft space. Other key players include:

- Bombardier Aircraft.
- Embraer Aircraft.
- Fokker.
- McDonnel Douglas.
- Mitsubishi.
- Sukhoi.
- Irkut.
- COMAC.

In addition to various brands, there are also several types of commercial aircraft, with respect to function and propulsion. Jet aircraft are by far the most common in terms of total market share, in part because mid-sized and large airplanes where most of the market lies are exclusively jet-based engines. However, turboprop engines are more common for smaller aircraft, particularly those used for short distance travel, for either passenger loads or for shipping.

Other categories of commercial aircraft include freighter, combination and convertible aircraft. Key manufacturers include Boeing and Airbus, as well as McDonnell Douglas and Bombardier.

General Aviation

The general aviation category includes mostly smaller planes that are generally not used for commercial transport or large-scale movement of passengers. General aviation, as defined in this study, includes the following airplane categories:

- Very light jets.
- Light business jets.
- Mid-size business jets.
- Heavy business jets.
- Private single engine.
- Twin turboprops.

The general aviation category supports various charter-run businesses, as well as private aircraft that are used for business. The category also includes very small recreational craft and transport craft, as well as local commercial and public use aircraft. These include small-scale government patrols, local rapid transport and small-scale general service operations.

Helicopters

The commercial helicopter market is strongly decoupled from commercial passenger and cargo aircraft markets and is driven by wholly different global market trends and influencing factors. A large segment of the global helicopter market is supported by the oil industry, particularly by the offshore oil and gas industry. Helicopter is the transport method of choice for moving staff and small- to mid-sized items, supplies and equipment to and from oil and gas rigs that are located offshore.

Helicopters are also used for other purposes and end uses, including:

- General transport of people and cargo.
- Medical transport.
- Construction.
- Search and rescue.
- Tourism.
- Agriculture, including crop application.
- Law enforcement.
- Aerial observation.
- Recreation.
- Scientific purposes.

Defense Industry and Government

Defense industry includes cargo and transport applications, for which the same or very similar technologies can be used as compared to commercial aviation, general aviation or helicopters. Military equipment is typically more specialized, and often manufactured separately from other commercial end products. Military and defense specific applications can Include military jets, military turboprops, military helicopters, and military amphibious planes and helicopters. Military jets are typically supersonic fighter jets that are used primarily to bomb strategic targets on the ground or otherwise engage with military targets. These jets cost billions of dollars to develop (development costs are not included in this study), and they are typically deployed from air force bases and navy carriers.

Defense industry and government also includes defense-specific applications. These include missiles rockets and other similar equipment and applications. These advanced design systems are specialty systems designed explicitly for the global defense industry.

Commercial Space Industry

The commercial space industry currently focuses primarily on satellite placement and launch. In fact, today's commercial space industry derives the vast majority of its revenues from launching satellites into space. Presently, it is primarily commercial launch providers that are responsible for putting government and commercial/private satellites into orbit. The commercial space industry is allowed only to launch from specific sites globally, with multiple sites in the U.S., as well as launch sites in China and Russia.

Well-publicized space industry activity associated with the International Space Station and other manned and research missions are the subject of much public outreach and interest. However, these activities actually represent only a small fraction of the overall activities in this segment. Increasingly, there has been interest from global superpowers, the U.S., China and Russia in particular, to start moving a greater portion of their defense logistics toward space. These efforts are presently still negligible in terms of revenue generation, but can be expected to increase more substantially, particularly five to 10 years from now.

Materials Not Considered in this Chapter

There are several materials of interest including those that could someday capture significant market share that have not yet developed to the point of achieving significant market share. The other materials listed here are similar to the aerospace materials, however they are not considered emerging technologies in the industry.

- Conventional steel plate, carbon steel and other conventional metals that are used in some cases for basic structural elements.
- Carpeting, vinyl, foams, and other non-structural cabin elements that use conventional materials.
- Pure aluminum (only aluminum alloys are considered in this study).

Chapter 9

Company Profiles

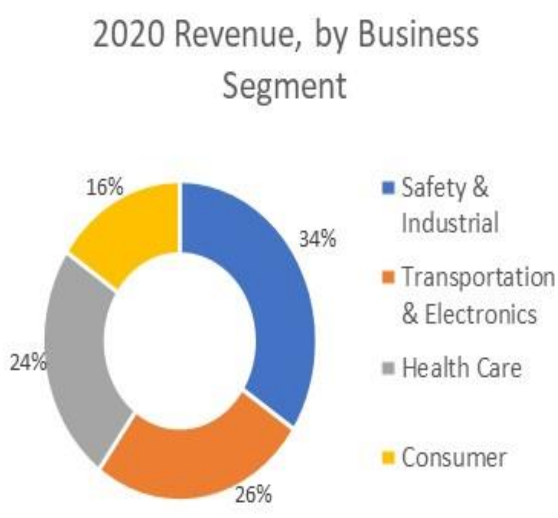
Chapter 9: Company Profiles

3M

3M Corporate Headquarters
3M Center
St. Paul, MN 55144-1000
Tel: 888/364-3577
Website: www.3m.com

3M is a leading member of the Fortune 500 and is a multinational conglomerate corporation. The company was founded in 1929. The company operates in four major segments: safety and industrial, transportation and electronics, healthcare, and consumer. The company primarily markets its aerospace ceramics and composites under transportation and electronics segment, in its advanced materials subsegment. It also provides composite part solutions to the aerospace industry in the transportation business segment.

Figure 59
3M Co.: Financial Overview, 2020
($ Millions)



Source: Annual Report 2020

The ceramic and composite product range of the company includes films, ceramic fibers, woven fabrics, tapes, and yarns marketed under the brand name Nextel. These ceramic fibers and textiles satisfy the thermal, mechanical and electrical performance requirements from the U.S. FAA for aircraft firewalls and U.S. NASA standards for shuttle launch and re-entry. They provide consistent and reliable performance in critical applications such as aircraft wiring insulation, engine firewalls and spacecraft shields. Nextel ceramic fibers are also used as structural reinforcements in metal, ceramic and polymer composites materials.

ADVANCED COMPOSITES INC.

2575 S 3270 W
Salt Lake City, UT 84119
Tel: 801/467-1204
Website: www.advancedcomposites.com

Advanced Composites Inc. is a leading manufacturer of aerospace composite structures, primarily for the defense industry, using carbon and glass fibers. The company is also involved in filament winding, compression molding and reaction injection molding, and lay-up compositing processes. Advanced Composites Inc. has partnered with various leading aircraft manufacturers to provide critical composite parts for their aircraft, including the Boeing C-17, Boeing 787 Dreamliner and Airbus A400M.

APPLIED CERAMICS

48630 Milmont Dr.
Fremont, CA 94538
Tel: 510/249-9700
Website: www.appliedceramics.net

Applied Ceramics Inc. is a U.S.-based ceramic component manufacturing company with a presence in Europe (Croatia) and Asia (Japan and Taiwan). The company provides aerospace-grade products made from advanced ceramics. The materials include oxide ceramics such as alumina, zirconia, aluminum titanate; and non-oxide ceramics such as silicon nitride, silicon carbide, and aluminum nitride.

CERAMCO INC.

1467 E Main St.
Center Conway, NH 03813
Tel: 603/ 447-2090
Website: www.ceramcoceramics.com

Ceramco Inc. offers thermal, electrical and structural applications of ceramics to the aerospace industry. Its product range covers alumina, zirconia, silicon nitride, mullite, and custom ceramics. The company works with leading players in the aerospace ceramics market such as 3M, Boeing, GE Aviation, NASA, Northrop Grumman, Raytheon, and Rolls-Royce.

COMPOSITE HORIZON LLC

1471 W Industrial Park St.
Covina, CA 91722
Tel: 626/331-0861
Website: www.chi-covina.com

Composite Horizon has been supplying advanced aerospace composites for the past 40 years. The company is a leading manufacturer of lightweight aerospace composites, composite aircraft structures and assemblies. Its oxide ceramic and composite parts can be used in engines, airframe structures and space vehicles.

COORSTEK

14143 Denver West Pkwy.
Golden, CO 80401
Tel: 303/271 7000
Website: www.coorstek.com

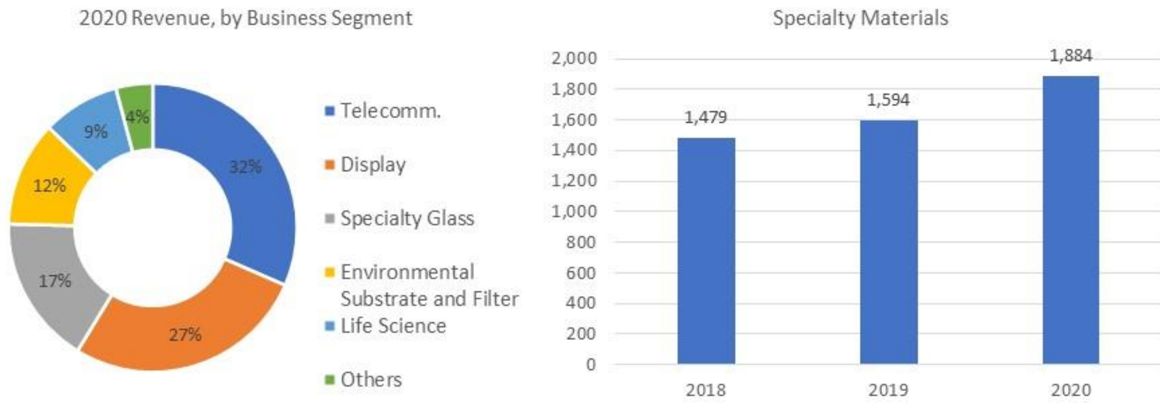
CoorsTek Inc. is a private organization and ranks among top technical ceramic manufacturers in the world. The company serves the aerospace, automotive, chemical, electronics, medical, metallurgical, oil and gas, and semiconductor industries. For the aerospace and defense segment, its product lines cover a variety of critical components, armor panels (CeraShield) and optics. The materials include alumina, alumina nitride, boron carbide, silicon carbide, silicon nitride, zirconia, and composites.

CORNING INC.

One Riverfront Plaza
Corning, NY 14831
Tel: 607/974-9000
Website: www.corning.com

Corning started as a glass business more than 160 years ago, and over time expanded into optical communications, mobile consumer electronics, display technology, automotive emissions control, laboratory products, and other glass products. The company has production plants located in 15 countries across the globe.

Figure 60
Corning: Financial Overview, 2020
($ Millions)



Source: Annual Report 2020

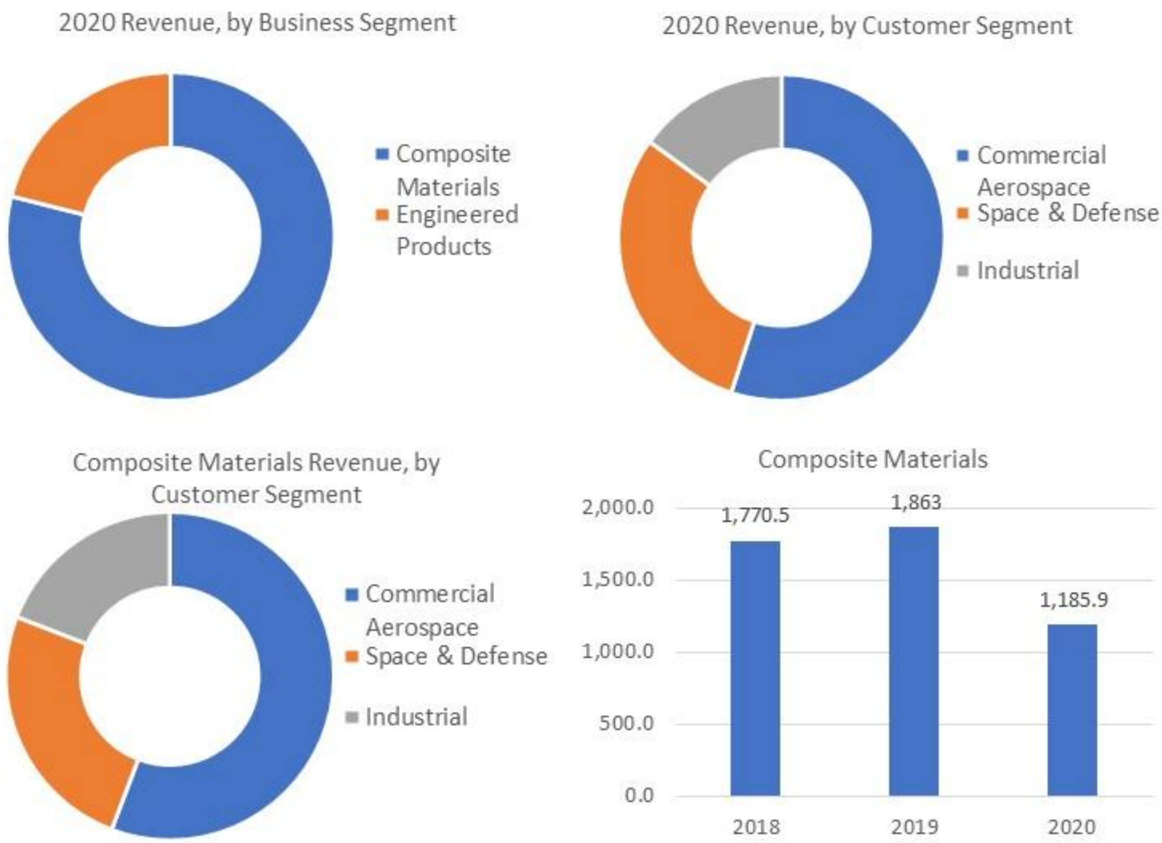
The reportable business segments of the company are Display Technologies, Optical Communications, Environmental Technologies, Specialty Materials, and Life Sciences. The specialty materials segment deals with ceramics and composites in the aerospace industry.

HEXCEL

281 Tresser Blvd., 16th Fl.
Stamford, CT 06901
Tel: 203/969-0666
Website: www.hexcel.com

Hexcel is a leading supplier of carbon-based composites in the aerospace industry. Founded in 1948, the company has 23 plants supplying carbon fiber reinforcements, resin systems and honeycomb structures to the aerospace industry.

Figure 61
Hexcel: Financial Overview, 2020
($ Millions)



Source: Annual Report 2020

The reportable business segments of the company are composite materials and engineered products. The Composite Materials segment manufactures and markets carbon fibers, fabrics and specialty reinforcements, and prepregs, along with other fiber-reinforced matrix materials, structural adhesives, honeycomb, molding compounds, and tooling materials. The Engineered Products segment manufactures and markets composite structures and precision machined honeycomb parts primarily for use in the aerospace industry.

HONEYWELL INTERNATIONAL

300 S Tryon St., Ste. 500
Charlotte, NC 28202
Tel: 877/841-2840
Website: www.aerospace.honeywell.com

Honeywell International is a U.S.-based conglomerate conducting business in Aerospace, Honeywell Building Technologies, Performance Materials and Technologies, and Safety and Productivity Solutions. The aerospace segment of the company is a leading supplier of products, software and services for aircraft in the global market. The client base of the business unit consists of OEMs such as regional and business aviation aircraft, aircraft operators, and defense and space contractors. Honeywell is a leading supplier of MRO services for engines. With its expertise in the segment, the company developed its proprietary Thermal Barrier Coating (TBC) systems.

Figure 62
Honeywell International: Financial Overview, 2020
($ Millions)

Source: Annual Report 2020

INTERNATIONAL SYALONS

Stephenson St.
Willington Quay
Wallsend, NE28 6TT
U.K.
Tel: +44 191 295 1010
Website: www.syalons.com

International Syalons is a U.K- based company with expertise in engineering technical ceramics for extreme environments. Though the company focuses on developing silicon nitride-based ceramics, its product portfolio also includes alumina, zirconia and silicon carbide ceramics. These ceramics find applications in thermal insulation and structural parts in the aerospace industry.

KYOCERA FINECERAMICS PRECISION GMBH

Lorenz-Hutschenreuther-Strasse 81
95100 Selb
Germany
Tel: +49 9287 807-0
Website: www.kyocera-precision.com

KYOCERA Fineceramics Precision GmbH is German ceramic and composite component manufacturer with products such as nozzles, funnels, plugs, lightweight structures, and custom parts. The company markets high-performance ceramics such as alumina, zirconia, silicon nitride, silicon carbide, and aluminum titanate under the variants of its brand StarCeram.

MCDANEL ADVANCED CERAMIC TECHNOLOGIES LLC.

510 Ninth Ave.
Beaver Falls, PA 15010
Tel: 724/843 8300
Website: www.mcdanelceramics.com

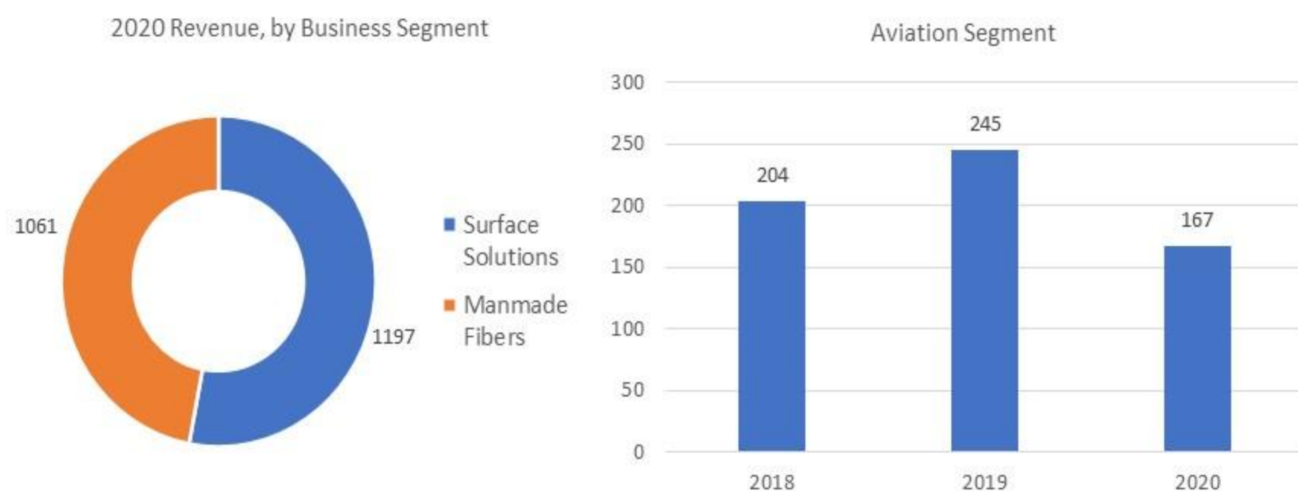
McDanel Advanced Ceramic Technologies LLC has been in the business of ceramics and components for more than 100 years. The company's product portfolio includes components and tubes made from advanced ceramics such as high purity alumina, mullite, fully stabilized zirconia, and sialon.

OERLIKON METCO

Churerstrasse 120
8808 Pfäffikon
Switzerland
Tel: +41 58 360 9696
Website: www.oerlikon.com

Oerlikon Metco is a global technology group founded in 1906. The company mainly operates in two business segments: surface solutions and manmade fibers. The company caters to the aerospace industry with its advanced materials, functional coatings and process technologies. Oerlikon is a leading supplier of thermal barrier coatings and environmental barrier coatings for engines and aircraft parts.

Figure 63
Oerlikon Metco: Financial Overview, 2020
(CHF Millions)



Source: Annual Reports 2020, 2019

SAINT-GOBAIN

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12 place de l'Iris
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Saint-Gobain is an international conglomerate catering the aerospace ceramics and composites demand around the world. The company has five reporting business segments: Northern Europe, Southern Europe, Middle East and Africa, high-performance solutions, and Americas. The high-performance solutions segment looks after the aerospace ceramics and composites business for the company. The segment provides thermal barrier coatings and environmental barrier coatings. Also, the company acquired HyComp, a leading supplier of carbon fiber composite components and thermoplastic materials suitable for applications in the aerospace industry, thereby expanding its product and service portfolio for the aerospace ceramics market.

Figure 64
Saint-Gobain: Financial Overview, 2020
(€ Millions)

Source: Annual Reports 2020, 2019

Appendix

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Appendix: Acronyms

Table 77
Acronyms Used in This Report

Abbreviation	Defination
ADD	Agency for Defence Development
BMC	Bulk molding compound
CEMAC	Monetary and Economic Community of Central Africa
CF	Carbon fiber
CFRP	Carbon fiber-reinforced polymer
CMC	Ceramic matrix composite
COMAC	Commercial Aircraft Corp. of China
CVD	Chemical vapor deposition
EBC	Environmental barrier coating
FRP	Fiber-reinforced plastic
GFRP	Glass fiber-reinforced polymer
GLARE	Glass laminate aluminum reinforced epoxy
GMT	Glass mat-reinforced thermoplastics
ITC	International Trade Centre
LFT	Long fiber-reinforced thermoplastics
MRO	Maintenance, Repair and Operation
RT	Room temperature
RTM	Resin transfer molding
SMC	Sheet molding compound
TBC	Thermal barrier coating
TGO	Thermally grown oxide coat
TPS	Thermal protection system
UAS	Unmanned Air System
UAV	Unmanned Aerial Vehicle
USMC	United States–Mexico–Canada
USMCA	United States–Mexico–Canada Agreement
YSZ	Yttria stabilized zirconia

Source: BCC Research

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