Advanced Materials for Extreme Environments:

Global Markets

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Chapter 1

Introduction

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Chapter 1: Introduction

Study Goals and Objectives

Advanced materials for extreme environments track their origin to the 1950s when the first ultrahigh-temperature melting borides were introduced in nuclear reactors. About a decade later, these materials became of interest in the aerospace industry for fabrication of propulsion systems and atmospheric re-entry vehicles. Eventually, advanced ceramic materials for extreme environments gained increasing interest not only for their resistance at very high temperatures but also for other properties, such as elevated hardness and durability. As a result, the use of these materials rapidly expanded beyond the aerospace, defense and energy sectors and into other industries, including the mechanical and metallurgical fields.

The development of advanced composite materials for extreme environments and the introduction of new fabrication processes helped to overcome several issues related to the manufacturing of these products, facilitating the diffusion of these materials in various industrial applications and contributing to create a multibillion dollar market.

The main goal of this report is to provide an updated review of the most important advancements in technologies for advanced materials for extreme environments, with a focus on those materials, products, and processes that will be instrumental to market growth during the next five years. In addition, a current and detailed assessment of the market for advanced ceramic materials for extreme environments is offered, including an objective analysis of industry and technological trends, and prospects for future growth.

Specifically, the major objectives of this study are to:

- Provide a detailed review of advanced ceramic materials for extreme environments, focusing on materials, properties, configurations, fabrication technologies and applications.
- Highlight new technological developments related to advanced ceramic materials for extreme environments, while outlining current technical issues.
- Review existing fields of application for advanced ceramic materials for extreme environments and examine emerging applications.
- Estimate current global markets for advanced ceramic materials for extreme environments by material group, composition, microstructure, configuration, application, and region, with growth forecasts through 2025 for each market segment.
- Identify important technology and industry trends within each market segment.
- Offer an updated review of current industry players, including manufacturers of advanced ceramic products, raw materials and fabrication equipment, technology developers, and future market participants.
- Provide a description of the most relevant research and development activities.
- Determine trends in recently issued U.S. patents.

Reasons for Doing This Study

Advanced materials for extreme environments include three main groups of materials characterized by very high temperature resistance. Due to their chemical structure and manufacturing process, these materials also exhibit other properties such as oxidation resistance and chemical stability at high temperatures, exceptional hardness, and low thermal expansion. These characteristics are utilized in many applications requiring operation under extreme conditions (e.g., very high temperatures and oxidative environments) and/or superior wear and corrosion resistance.

Advanced materials for extreme environments are fabricated using various technologies and are available in the form of pure materials (i.e., monoliths) or as composites. Composites are the most common type since they allow for more flexibility in the fabrication process and help to solve some of the manufacturing issues occurring with monoliths.

The global market for advanced ceramic composites for extreme environments is estimated to be valued at $24.4 billion in 2020 and projected to expand at a compounded annual growth rate (CAGR) greater than 10% through the next five years. Advanced ceramic composites for extreme environments represent a small but still significant share of this market.

Increasing market penetration of advanced materials for extreme environments can be attributed to different factors, including their peculiar properties, new emphasis on space exploration, ongoing need for advanced defense systems and engines with higher fuel efficiency, as well as fabrication of tools with higher durability for metal working

In addition, new applications for advanced materials for extreme environments are emerging. Of particular relevance to future market growth is their increasing utilization in the energy sector for devices such as solid oxide fuel cells, thermoelectric generators, and absorbers for concentrated solar plants.

The principal reason for doing this study is to present a current assessment of advanced ceramic materials for extreme environments from both a technological and market point of view, and to outline future trends and key developments.

There is also a need to evaluate the current status and future trends of this market from a global standpoint. As the use of these products expands and new fields of application emerge, information on the suppliers and developers of advanced materials for extreme environments and their regional distribution becomes more valuable.

An equally important reason for undertaking this study is to provide technical insights into advanced materials for extreme environments by:

- Providing a review of materials, applications, and production methods.
- Identifying current technological trends.
- Providing an overview of the main global R&D activities related to advanced materials for extreme environments, resulting in the issuance of patents.
- Illustrating the latest technological developments.

This information can assist companies in identifying opportunities for process and productivity improvements and new product development, resulting in a positive impact on future market growth.

Intended Audience

This study will be of primary interest to all organizations that:

- Develop, manufacture, sell, and distribute advanced materials for extreme environments.
- Supply raw materials for production of advanced ceramic materials for extreme environments.
- Manufacture process equipment utilized by producers of advanced ceramic materials for extreme environments.
- Provide technical and/or marketing services in conjunction with the above-mentioned products.
- Are planning to enter the market for advanced materials for extreme environments as a supplier, manufacturer, service provider, or end-user.

Overall, this study applies to industry sectors such as aerospace, defense, energy, mechanical/chemical, metallurgical, healthcare, and electronics.

The study is mainly directed toward executives, directors, operations managers, sales and marketing managers, and strategic planners working within the above industry sectors. Universities and research facilities may also find this study to be a good source of technical information regarding technology and applications in advanced materials for extreme environments, which can be used as a baseline for new or expanded R&D activities. Librarians of technical information and research centers can also use this report to provide critical data to product managers, market analysts, researchers, and other professionals needing detailed and updated insights into this field.

Scope of Report

This report provides an updated review of advanced ceramic materials for extreme environments, including materials and production processes, and identifies current and emerging applications for these products.

BCC Research delineates the current status of the market for advanced ceramic materials for extreme environments, defines trends, and presents growth forecasts for the next five years. The market for advanced materials for extreme environments is analyzed based on the following segments: material group, composition, microstructure, configuration, application, and region. In addition, technological issues, including key events and the latest developments, are discussed.

More specifically, the market analysis conducted by BCC Research for this report is divided into five sections.

In the first section, an introduction to the topic and a historical review of the technologies of advanced materials for extreme environments are provided, including an outline of recent events. In this section, current and emerging applications for advanced ceramic materials for extreme environments are also identified and grouped in segments (aerospace and defense, energy, mechanical/chemical/metallurgical, and others).

The second section provides a technological review of advanced ceramic materials for extreme environments. This section offers a detailed description of advanced materials for extreme environments, their properties, configurations, and typical fabrication methods. This section concludes with an analysis of the most important technological developments since 2016, including examples of significant patents recently issued or applied for. The chapter ends with a highlight of the most active research organizations operating in this field and their activities.

The third section entails a global market analysis for advanced ceramic materials for extreme environments. Global revenues (sales data in millions of dollars) are presented for each segment (material group, composition, microstructure, configuration, application, and region), with actual data referring to the years 2018 and 2019, and estimates for 2020. Dollar figures refer to sales of these products at the manufacturing level.

The analysis of current revenues for advanced ceramic materials for extreme environments is followed by a detailed presentation of market growth trends, based on industry growth, technological trends, and regional trends. The third section concludes by providing projected revenues for advanced ceramic materials for extreme environments within each segment, together with forecast CAGRs for the period 2020 through 2025. Projected and forecast revenue values are in constant U.S. dollars, unadjusted for inflation.

In the fourth section of the study, which covers global industry structure, the report offers a list of the leading manufacturers of advanced ceramic materials for extreme environments, together with a description of their products. The analysis includes a description of the geographical distribution of these firms and an evaluation of other key industry players. Detailed company profiles of the top players are also provided.

The fifth and final section includes an analysis of recently issued U.S. patents, with a summary of patents related to advanced materials for extreme environments, fabrication methods, and applications. Patent analysis is performed by region, country, assignee, patent category, material type, material group, and application.

Methodology and Information Sources

To analyze the overall market and market segments, both primary and secondary research methodologies were used to obtain market data.

The technology section of this report is based on information derived from technical literature, related BCC Research reports, professional journals, the author's field experience, and online sources.

Global market analysis, which is based on a combination of bottom up and top down methods, was performed by a thorough investigation of manufacturers of advanced ceramic materials for extreme environments, material suppliers, producers of fabrication equipment, and developers of new technologies.

Data were obtained from the direct contribution of primary sources, including company executives, managers, engineers and other technical personnel representing manufacturers, developers, and users of advanced ceramic materials for extreme environments; producers of related materials and equipment; representatives of academia and trade associations; and industry market analysts.

Additional data for each company were obtained by thoroughly analyzing Security and Exchange Commission (SEC) filings, websites, annual reports, industry directories, industry magazines and catalogs, government sources, and other public sources.

Secondary sources of information include, but are not limited to:

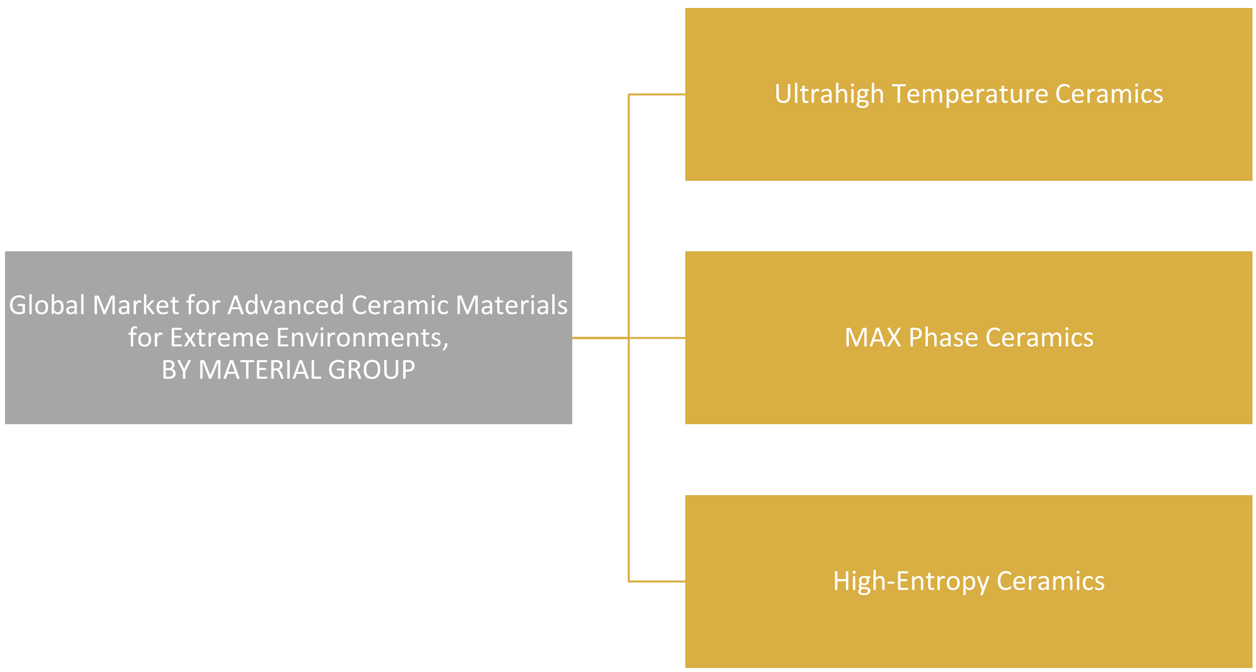
- U.S. Securities and Exchange Commission Filings.
- U.S. Patent and Trademark Office.
- European Patent Office.
- Company websites.
- Company annual reports.
- Thomas Register.
- Moody's Directory.
- S&P Industry Survey.
- Dun & Bradstreet Business Directory.
- Foreign Chamber of Commerce Directories.
- Foreign Stock Exchange Listings.
- American Ceramic Society Publications.
- American Chemical Society Publications.
- Public library online services for businesses.

In addition to utilizing the above primary and secondary sources, market growth trends and forecasts were compiled by gaining additional insights from relevant financial and market information, related BCC Research reports, and the author's own in-depth and comprehensive analysis of the collected information.

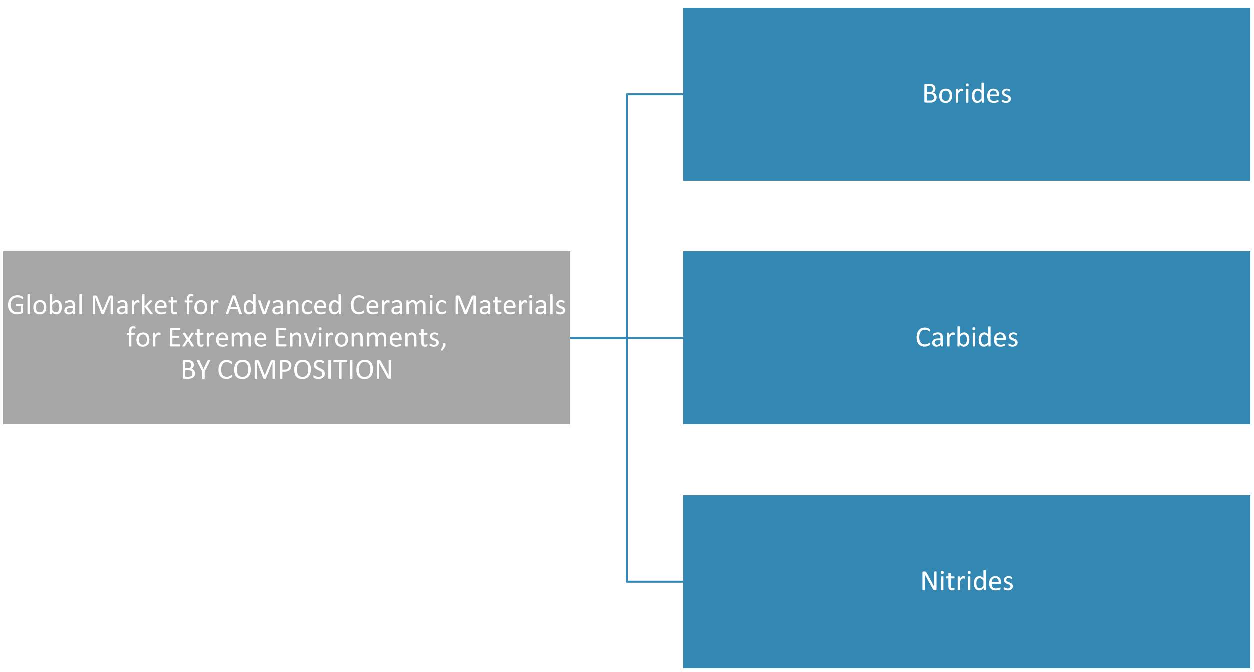
Market Breakdown

In this report, the market for advanced ceramic materials for extreme environments is analyzed based on the following categories:

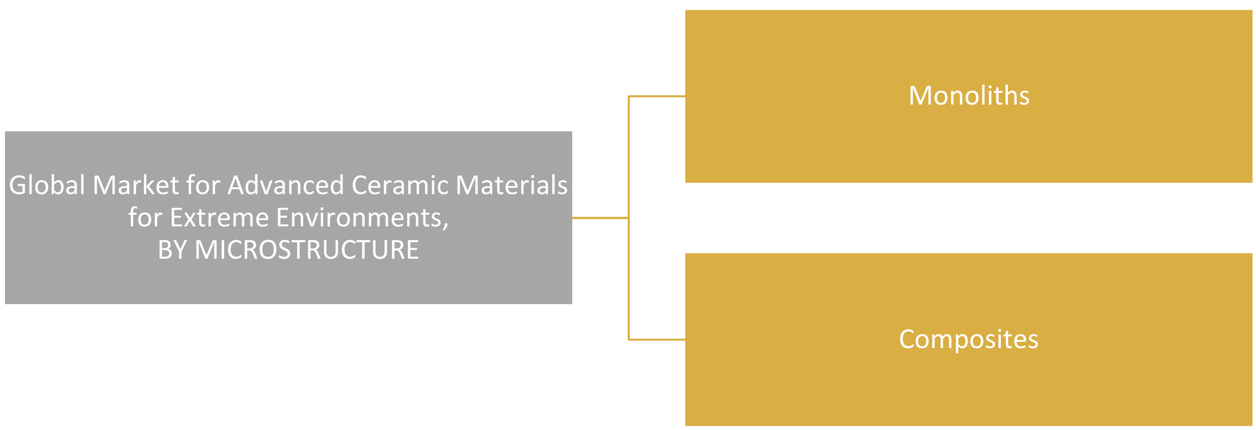
Global Market for Advanced Ceramic Materials for Extreme Environments, by Material Group



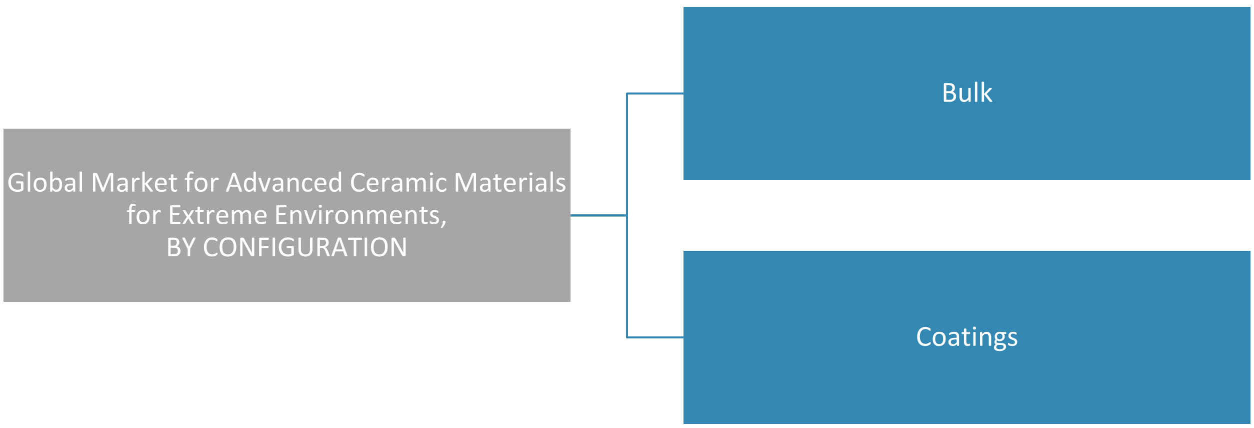
Global Market for Advanced Ceramic Materials for Extreme Environments, by Composition



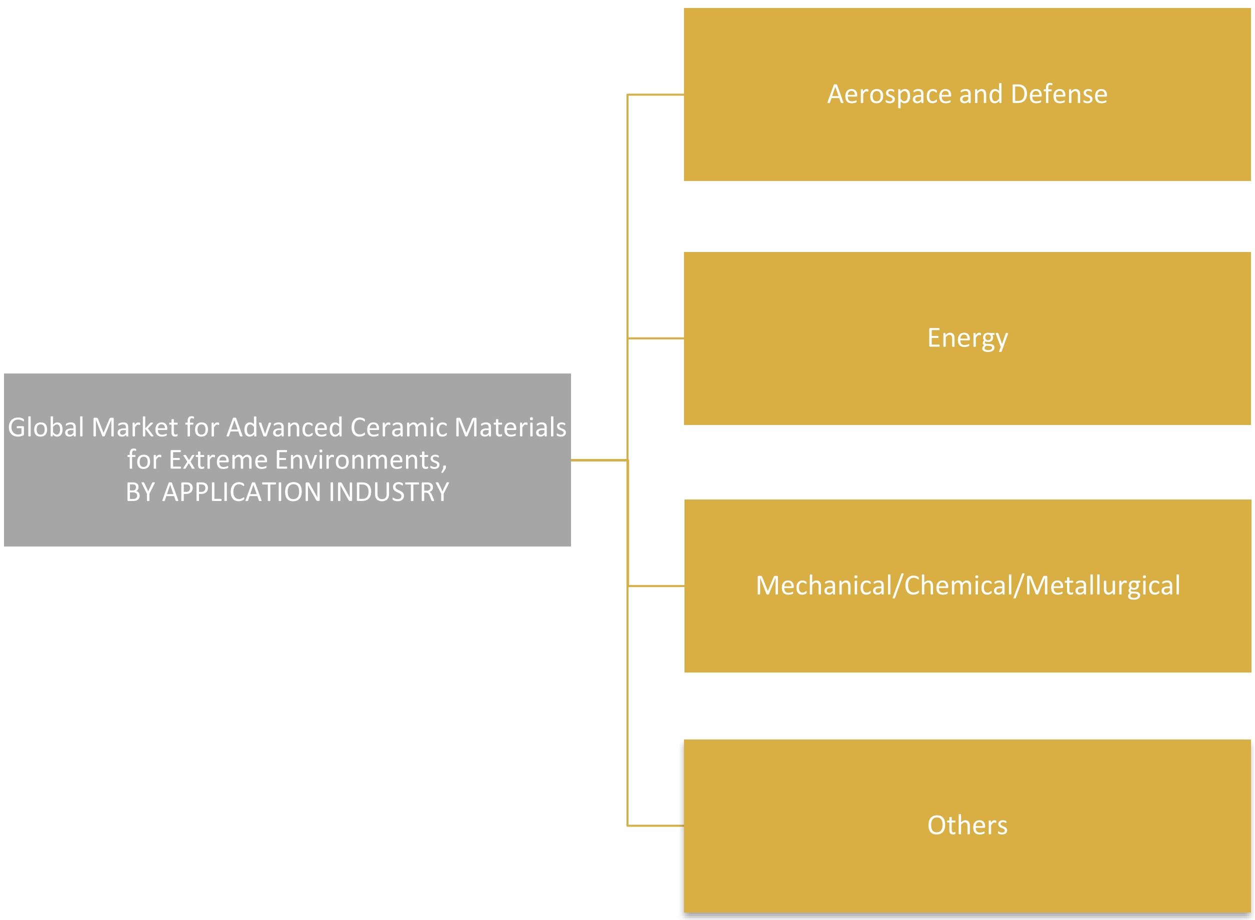
Global Market for Advanced Ceramic Materials for Extreme Environments, by Microstructure



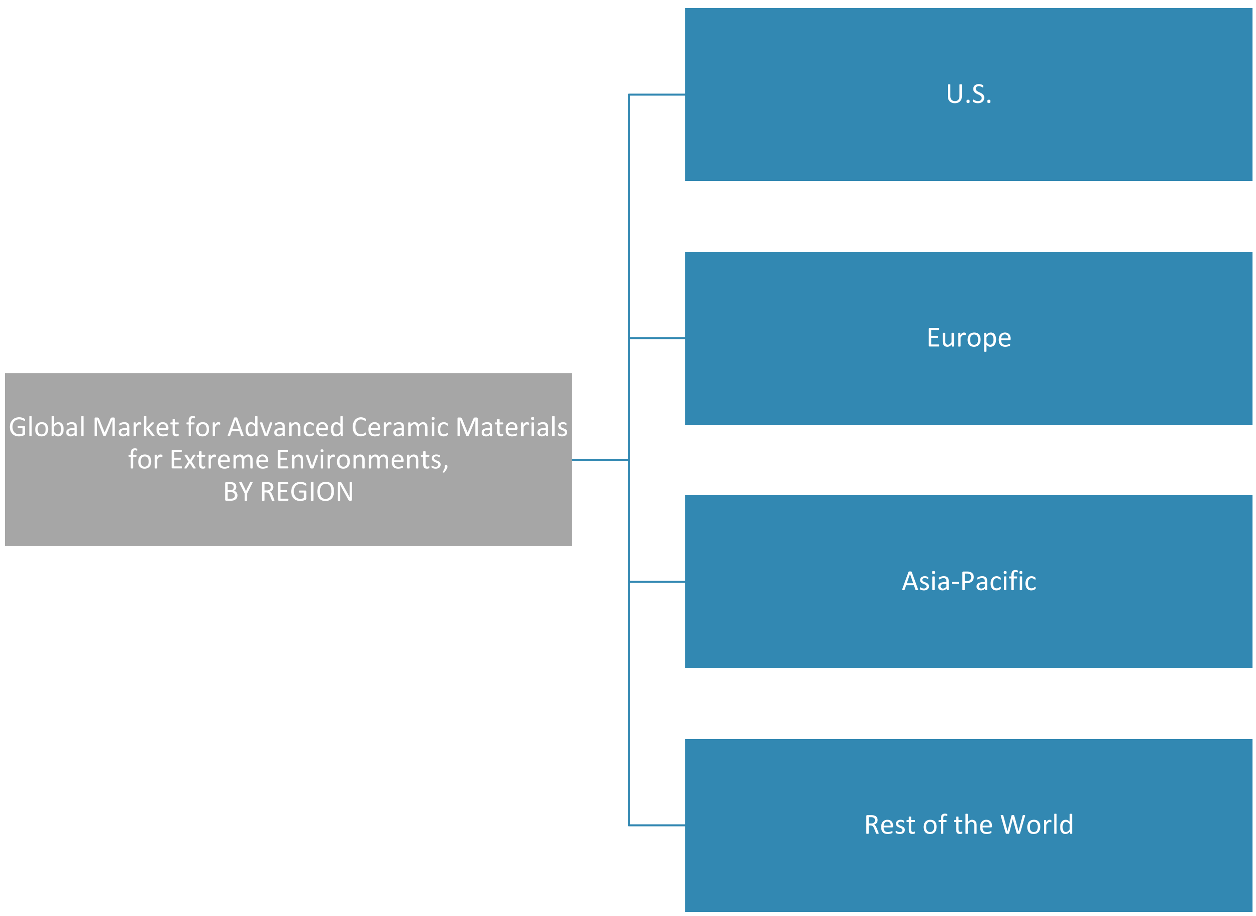
Global Market for Advanced Ceramic Materials for Extreme Environments, by Configuration



Global Market for Advanced Ceramic Materials for Extreme Environments, by Application Industry



Global Market for Advanced Ceramic Materials for Extreme Environments, by Region



Analyst's Credentials

Margareth Gagliardi, Chief Research Analyst in Advanced Materials for BCC Research, has more than 30 years of experience in the field of advanced materials, specializing in ceramic formulations, materials processing, and new product development. After receiving her degrees in Chemical and Ceramic Engineering, she worked in both manufacturing and R&D holding senior management positions within U.S. and European firms producing electronic, mechanical, chemical, and structural components.

She is currently focusing on market intelligence and advanced technologies analysis for organizations and research institutions that operate within a range of high-tech industries.

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Related BCC Research Reports

- AVM189A *Ceramics Markets: a BCC Research Outlook.*
- AVM016H *Sol–Gel Processed Ceramics and Glass: U.S. Markets to 2023.*
- NAN015J *Advanced Ceramics and Nanoceramic Powders.*
- EGY175A *Generation IV Reactors and Advanced Materials: Emerging Opportunities.*

Chapter 2

Summary and Highlights

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Chapter 2: Summary and Highlights

Advanced materials for extreme environments are a group of materials characterized by distinct properties suitable for applications requiring resistance to ultrahigh temperatures, oxidation and corrosion, high mechanical stresses, intense wear and other unusual conditions. The most common advanced ceramic materials for extreme environments are based on borides, carbides, and nitrides of group IV and V transition metals. These materials have very high melting points (3000°C or higher) in their pure form.

BCC Research has identified a number of sectors in which advanced materials for extreme environments find current and potential applications, including aerospace, defense, energy, mechanical, chemical, and metallurgical.

This study provides an updated review of the technologies of advanced ceramic materials for extreme environments, including materials, properties, configurations, fabrication processes, and applications. It also offers a detailed market analysis for these products by segment (material group, composition, microstructure, configuration, application, and region), describing technical aspects and trends that will affect future growth of this market.

As shown in the Summary Table, the global market for advanced ceramic materials for extreme environments increased from $2.9 billion in 2018 to $3.0 billion in 2019, and is estimated to drop to $2.9 billion in 2020, as a consequence of the economic slow-down due to the COVID-19 pandemic.

Mechanical/chemical/metallurgical applications currently account for the largest share of the market, at an estimated 92.7% of the total in 2020, corresponding to $2.7 billion. Within this segment, advanced ceramic materials for extreme environments are being used primarily for fabrication of super-hard wear and corrosion resistant components, parts for high-temperature furnaces, and sputtering targets for hard coatings. Sales of advanced materials for extreme environments for the metallurgical/chemical/mechanical sector are projected to rise at a CAGR of 5.6% during the 2020-2025 period.

By comparison, advanced ceramic materials for extreme environments for aerospace and defense represent a much smaller share at 5.3% of the total, corresponding to estimated 2020 revenues of $153 million. This segment has been expanding at a 0.7% CAGR since 2018, mainly driven by the use of advanced materials for extreme environments for production of aircraft components and military systems.

All the remaining applications currently account for an estimated 2.0% of the total market in 2020, with revenues of $57 million.

Sales of advanced ceramic materials for extreme environments are expected to continue rising at a single-digit rate during the next five years. Relevant factors that will be responsible for this growth are the following:

- General moderate growth of various industry sectors in which these materials find application.
- Improved manufacturing processes have been introduced, but difficulties and technical issues in the fabrication of these products still remain, which are preventing their widespread use for the most demanding applications.
- Low-cost fabrication processes, such as additive manufacturing, are being introduced and will provide a positive impact on market growth by facilitating production of components with tailored properties and complex geometries.
- New compositions, such as high-entropy ceramics, are projected to start commercialization only by the end of the forecast period.
- Emerging applications in the energy sector, such as for fabrication of concentrated solar power plants and fuel cells, will contribute to spur growth.

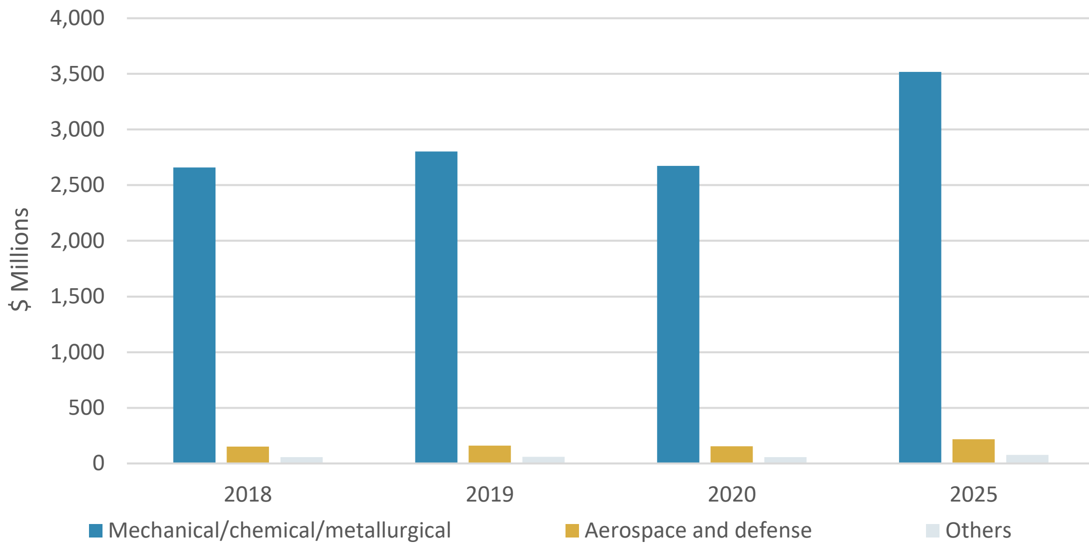
As a result, the total market for advanced ceramic materials for extreme environments is forecast to rise at a CAGR of 5.7% from 2020 to 2025, reaching global revenues of $3.8 billion in 2025.

Summary Table:
Global Market for Advanced Ceramic Materials for Extreme Environments, by Application Industry, Through 2025
($ Millions)

Application Industry	2018	2019	2020	2025	CAGR% 2020-2025
Mechanical/chemical/metallurgical	2,658	2,802	2,674	3,518	5.6
Aerospace and defense	151	161	153	217	7.2
Others	56	59	57	78	6.5
Total	2,865	3,022	2,884	3,813	5.7

Source: BCC Research

Summary Figure:
Global Market for Advanced Ceramic Materials for Extreme Environments,
by Application Industry, 2018-2025
($ Millions)



Source: BCC Research

Chapter 3

Market and Technology Background

bcc Publishing

Chapter 3: Market and Technology Background

Advanced Materials for Extreme Environments

Advanced materials for extreme environments represent a category of materials that are able to withstand unusually high temperatures, harsh oxidative and corrosive conditions, elevated stresses, and harmful radiations.

Advanced materials for extreme environments are gaining increasing importance for the creation of more advanced aerospace, chemical, mechanical, and energy technologies, such as jet propulsion components, space and re-entry vehicles, ultra-efficient aircrafts, high-efficiency turbines, fuel-saving internal combustion engines, durable batteries, self-healing structural components, lightweight structures, and new generations of chemical or nuclear reactors.

Advanced materials for extreme environments utilized for these applications are primarily ceramics and ceramic composites, which therefore are the focus of this study.

Ceramics

Ceramics are inorganic, non-metallic and polycrystalline materials. Glass is not included in this definition because it has an amorphous structure. Ceramics are typically differentiated according to two main categories based on end-use: traditional and technical products. Traditional ceramics consist of products that have been historically used in fields such as construction, decoration, furnishing, and food and beverages.

Technical (or engineered) ceramics, instead, include products used in sectors which expanded very rapidly after World War II, such as electronics, optoelectronics, energy, mechanical/chemical, aerospace and space exploration.

Ceramics for extreme environments belong to the category of technical ceramics and include primarily borides, nitrides and carbides. These materials are characterized by high melting point, outstanding hardness, and superior chemical stability.

Borides are typically applied where there is a need for higher oxidation resistance, whereas carbides and nitrides are mainly used for components designed to withstand high thermal and mechanical loads. Further details about these materials will be provided in the next chapter of this report ("Technology").

The Ceramic Industry

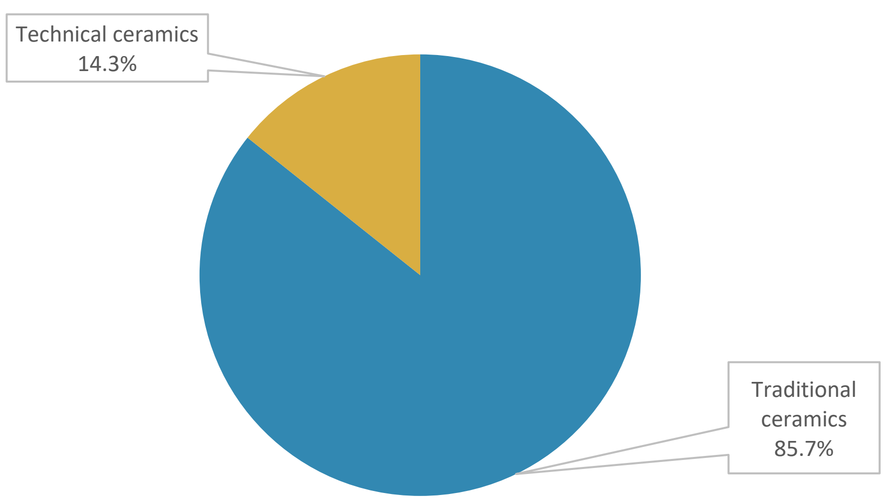
As shown in the table below, the ceramic industry is estimated to be valued at $696 billion in 2020 and projected to increase at a CAGR of 6.4% during the 2020-2025 period. Traditional ceramics currently account for the largest share of the market at 86.4% of the total, but technical ceramics represent the fastest growing segment with a CAGR of 7.4% during the next five years. This segment is projected to generate revenues of $136 billion by 2025, or 14.3% of the total.

Table 1
Global Market for Traditional and Technical Ceramics, by Category, Through 2025
($ Billions)

Category	2019	2020	2025	CAGR% 2020-2025
Traditional ceramics	626	601	812	6.2
Technical ceramics	98	95	136	7.4
Total	724	696	948	6.4

Source: BCC Research

Figure 1
Estimated Global Market Shares of Traditional and Technical Ceramics, by Category, 2025
(%)



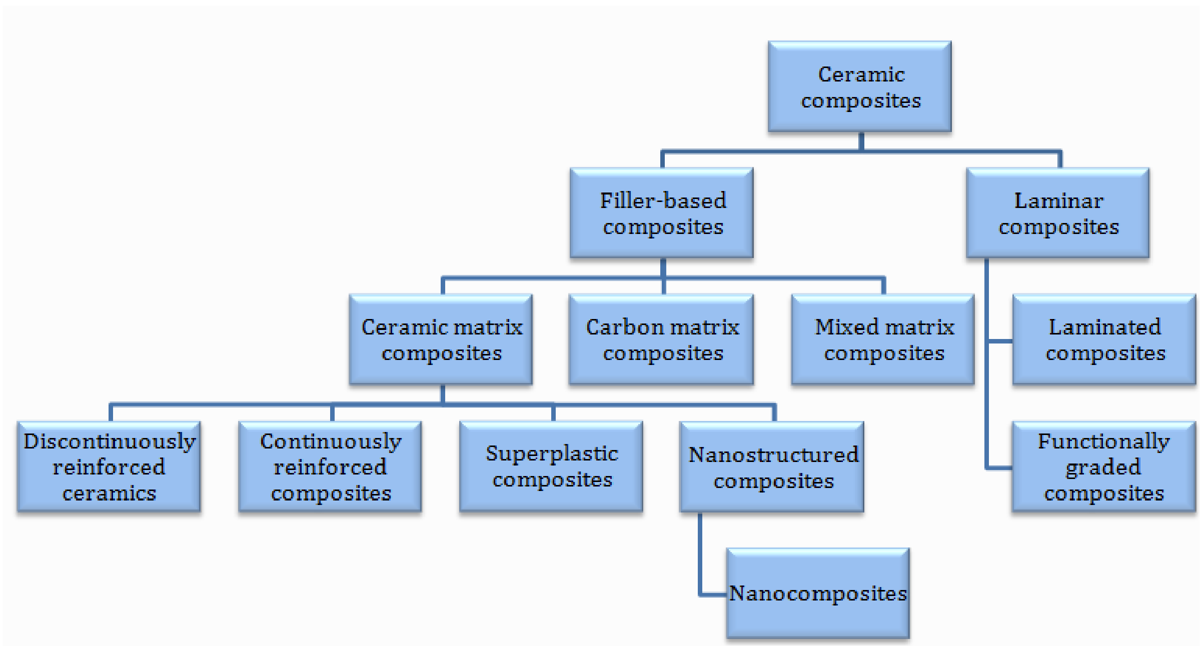
Source: BCC Research

Ceramic Composites

Ceramic composite is a general term indicating materials that are composed of at least two phases, in which the predominant phase is either a ceramic or a non-metallic, inorganic material such as carbon, glass or a glass-ceramic.

The next figure illustrates various types of ceramic composites that have been developed to date.

Figure 2
Schematic Diagram of Various Types of Ceramic Composites



Source: BCC Research

Filler-Based Composites

Filler-based composites have two components: the matrix material and the secondary phase (or filler). The matrix is by definition the predominant phase of a composite and represents the material whose properties are to be improved or modified. The secondary phase is the material utilized to modify the characteristics of the predominant phase. In most applications the secondary phase serves to improve the matrix's mechanical properties (e.g., toughness and thermal shock resistance). In these cases, the secondary phase is also known as the reinforcing phase.

However, the secondary phase can also be introduced to improve other properties of the matrix material such as bioactivity (in biocompatible ceramics) or electrical conductivity. Sometimes, more than one type of secondary phase is dispersed in the composite to improve the properties of the matrix material.

Composite materials are usually identified by the reinforcing phase followed by the name of the ceramic matrix, separated by a slash mark. For example: C/SiC indicates a carbon-reinforced SiC matrix. In other cases, the ceramic matrix material formula is placed before the symbol of the reinforcements separated by a hyphen. As an example, W/SiC/ZrB_2 is the same as ZrB_2-SiC-W.

Carbon matrix composites, in which the matrix material is typically amorphous carbon or graphite, currently account for the most popular type of ceramic composites, followed by ceramic matrix composites.

In mixed matrix composite, the matrix is composed of two or more materials, for example carbon and silicon carbide. Mixed matrix composites are for the most part still at the experimental stage.

Many advanced materials for extreme environments, however, belong to the ceramic matrix composite category. Traditionally ceramic matrix composites have been divided according to two main categories:

- Discontinuously reinforced composites (DRCs), in which the reinforcing phase is added to the matrix in the form of particles, platelets, whiskers, or chopped fibers.

- Continuously reinforced composites (CRCs), also known as continuous fiber ceramic composites (CFCCs). These composites contain long fibers or filaments arranged either randomly or unidirectionally or oriented in multiple directions (e.g., woven and braided), forming two or three-dimensional architectures.

In addition to DRCs and CRCs, more recently, superplastic and nanostructured composites have been introduced. Superplastic composites are materials able to withstand very high tensile deformation. These materials, which are typically obtained by colloidal processing, have very small grain size and are attractive for net-shape forming and for joining.

Nanostructured ceramic composites are materials in which one or both of the two phases are made of nanoparticles, whereas the term nanocomposite usually designates a nanostructured composite in which the secondary phase is nanosized, while the matrix is a micron-sized polycrystalline material. With on-going advancements in nanotechnology, development and fabrication of nanostructured ceramic composites has accelerated. Researchers are taking advantage of the unique properties of nanomaterials to create composites with characteristics tailored to very specific applications.

Nanostructured composites are growing in importance in the fabrication of advanced materials for extreme environments.

Laminar Composites
Laminar composites comprise two categories of materials: laminated composites and functionally graded composites. Laminated composites, which are also known as multilayer ceramics, are structures obtained by alternating different layers of two or more materials.

Functionally graded ceramic composites (FGCCs), instead, consist of two different materials with their composition changing gradually from one to the other. For the most part, FGCCs represent materials still under development. They have potential applications as rocket heat shields, heat exchanger tubes, and heat-resistant engine components.

The Ceramic Composite Market
The next table provides the market breakdown for ceramic composites by region. The U.S. and the Asia-Pacific region are the two largest players in this market. In the Asia-Pacific region sales of these materials are projected to reach revenues of $22.3 billion in 2025, corresponding to a 47.9% share of the total.

In the U.S., ceramic composites are estimated to generate 2025 revenues of $12.3 billion, or 26.3% of the total, whereas in Europe sales of these materials will account for 19.1% of the total market by the end of the forecast period.

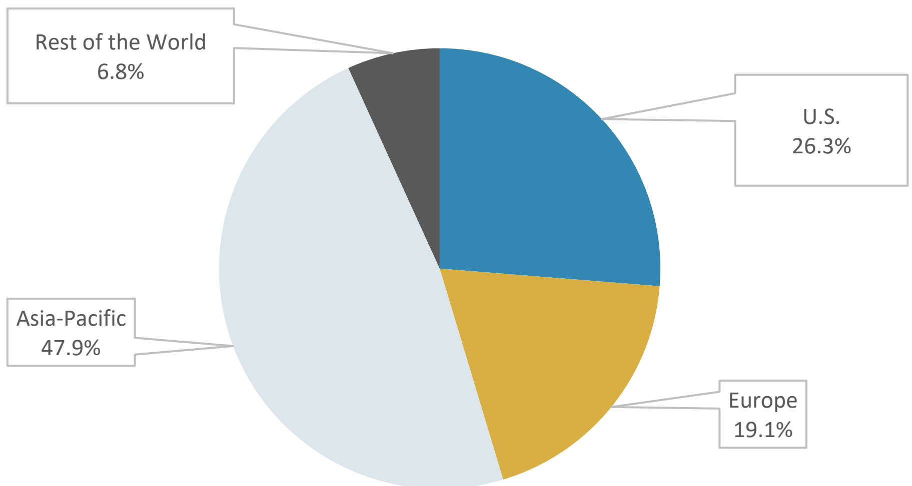
Rising at a very healthy CAGR of 13.9% during the next five years, ceramic composites are projected to be valued at $46.6 billion in 2025.

Table 2
Global Market for Ceramic Composites, by Region, Through 2025
($ Millions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	7,264	6,778	12,261	12.6
Asia-Pacific	11,423	10,952	22,337	15.3
Europe	5,376	5,011	8,889	12.1
Rest of the World	1,724	1,634	3,160	14.1
Total	25,787	24,375	46,647	13.9

Source: BCC Research

Figure 3
Estimated Global Market Shares of Ceramic Composites, by Region, 2025
(%)



Source: BCC Research

The scope of this report is to investigate how advanced materials for extreme environments are contributing to the expansion of the market for technical ceramics and ceramic composites by assessing the status of the development and utilization of advanced materials for extreme environments worldwide, investigating the critical factors and issues affecting their market growth, and outlining significant technological, industry, and regional trends that will impact this market in the near future.

Milestones in the History of Advanced Materials for Extreme Environments and Recent Events

The development of advanced materials for extreme environments can be traced back to the 1950s, when hafnium and zirconium boride were first studied for application in nuclear reactors.

During the early 1960s, the U.S. Air Force investigated these borides and other compounds for use as ultrahigh temperature ceramics (UHTCs) in rocket propulsion and atmospheric re-entry applications. Eventually, research related to UHTCs became funded also by NASA and the Navy. In particular, NASA scientists began studying these materials for construction of hypersonic vehicles during the Cold War and as part of the space race against Russia. However, the study of UHTCs was eventually abandoned as interest in the creation of hypersonic vehicles decreased in favor of other space programs.

In the 1960s, relevant work related to the development of ceramic matrix composite was also carried out resulting in the creation of reinforced ceramics and the introduction of the first commercial SiC whiskers. Particulate reinforced ceramics were produced with the purpose of creating cutting tools with improved wear-resistance and damage tolerance properties.

SiC whiskers were originally applied to metal matrices such as aluminum, but eventually their use was extended also to ceramic matrices to obtain composites characterized by high toughness and strength.

During the same period, H. Nowotny and his team at the University of Connecticut (Storrs, CT) discovered a group of materials consisting of ternary, layered carbides and nitrides with atypical mechanical properties. In 1996, M. Barsoum and his group at Drexel University (Philadelphia, PA) were able to synthesize a compound with similar structure having formula Ti_3SiC_2. They discovered that this family of materials (called MAX phases) exhibits a combination of properties of metals and ceramics.

In the 1970s and 1980s, various important breakthroughs occurred in the field of ceramic matrix composites. In 1973, it was demonstrated that the addition of platelets significantly improves the fracture toughness and thermal shock resistance of a monolithic material. Note: in this study, the term monolithic is used to indicate a product made only from one material, in opposition to composite, which contains two or more materials.

In 1976, Japanese scientists created SiC fibers with high tensile strength, and in 1982 researchers at Oak Ridge National Laboratory manufactured the first whisker-reinforced alumina composites.

During the 1980s, several toughening mechanisms for ceramic matrix composites were proposed. The theoretical basis for continuously reinforced ceramic matrix composites (CR-CMCs) was also established during this period. The combination of advances in micro-mechanical models and better knowledge of failure criteria, together with the introduction of enhanced processing methods and new types of fibers, led to the fabrication of CR-CMCs consisting of long fibers, a matrix, and an interface. Interfaces were based on pyrolytic carbon and boron nitride.

In the early 1990s, woven, braided, and other multi-directional fiber architectures were developed. Several major U.S. government/industry/academia programs were established to speed up commercialization of CFCCs.

In the late 1990s, NASA Ames resumed some programs aimed at creating fully reusable hypersonic vehicles. New research activities related to UHTCs were initiated, one of their main focus being the development of composites comprising a hafnium or zirconium boride matrix with a SiC reinforcement for sharp leading edges. At the same time, UHTCs began generating growing interest also for other applications, especially within the energy and metallurgical sectors.

At the end of the 1990s and the beginning of the new millennium, research related to advanced materials for extreme environments expanded at a rapid rate.

In 2004, disordered multicomponent systems with maximized entropy (high-entropy alloys) were discovered. These materials were found to possess some unique properties suitable for ground-braking applications. In 2012, high-entropy oxides were introduced and soon after other types of high-entropy ceramics were created (e.g., borides and carbides). These materials can be used for thermal barrier coatings, thermoelectric generators, catalysts, batteries, and wear- and corrosion-resistant parts.

A summary of the most important milestones related to advanced materials for extreme environments is provided in the table below.

Table 3
Technological Milestones for Advanced Materials for Extreme Environments

Period	Description
1950s	Hafnium and zirconium borides were first studied for application in nuclear reactors.
Early 1960s	The U.S. Air Force began the development of ultrahigh temperature ceramics for rocket propulsion and atmospheric re-entry applications.
Early 1960s	The first commercially available SiC whiskers were introduced.
Late 1960s	Particulate reinforced ceramics were introduced for cutting tools.
1960s	MAX phases were discovered.
1969	Carborundum Co. (Niagara Falls, NY) was awarded a patent for production of a carbon-carbon composite by impregnation.
1973	It was demonstrated that the addition of platelets significantly improved the fracture toughness and thermal shock resistance of monolithic materials.
1976	Japanese scientists synthesized silicon carbide fibers with high tensile strength, which were later manufactured and commercialized under the brand name Nicalon by Nippon Carbon (Tokyo, Japan).
1980s	Research of ceramic composites increased and the theoretical basis for continuous fiber ceramic composites (CFCCs) was also established.
1982	The first whisker-reinforced alumina composites were fabricated at Oak Ridge National Laboratory by hot-pressing.
Early 1990s	Woven, braided, and other multidirectional fiber architectures for CFCCs were developed.
1996	The MAX phase Ti_3SiC_2 was synthesized and found to exhibit a combination of properties of metals and ceramics.
Late 1990s	Research related to UHTCs resumed at NASA Ames.
1990 and beyond	Development of CMCs continued at a healthy speed, and a few military and industrial applications were commercialized. Research related to advanced materials for extreme environments also increased at a rapid rate.
2004	High-entropy alloys were discovered.
2012	High-entropy ceramics were created.

Source: BCC Research

The table and figure below show the number of global patent applications and patents issued (PAI) since 1990 that are related to advanced materials for extreme environments. The data clearly indicate that until the beginning of the 2000s, R&D activities in the field of advanced materials for extreme environments were running at a relatively low level with PAI of 32 or less per year globally. Conversely, since 2002, the number of applications and issued patents has been increasing steadily, reaching a peak in 2019, with 361 patents applied for or issued.

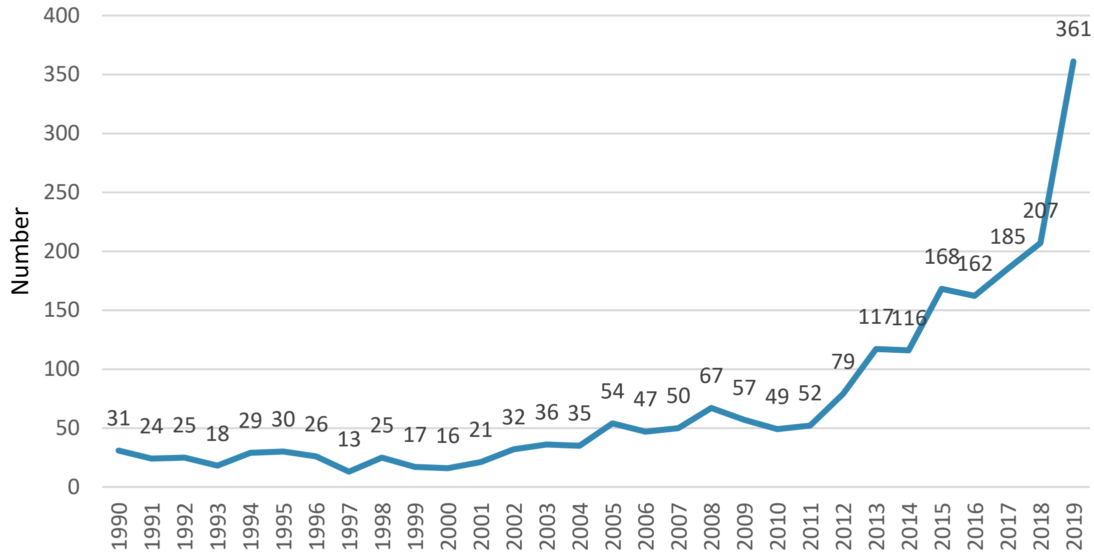
During the 2000-2019 period, PAI rose at a CAGR of 17.8%, and since 2010 the CAGR has been running at 24.8%, indicating that interest in the development of advanced materials for extreme environments is expanding at a very healthy rate.

Table 4
Global Patent Applications and Patents Issued on Advanced Materials for Extreme Environments, 1990-2019
(Number)

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
Number	31	24	25	18	29	30	26	13	25	17	238
Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
Number	16	21	32	36	35	54	47	50	67	57	415
Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Number	49	52	79	117	116	168	162	185	207	361	1,496

Source: BCC Research

Figure 4
Global Patent Applications and Patents Issued on Advanced Materials for Extreme Environments, 1990-2019
(Number)



Source: BCC Research

Current and Emerging Applications for Advanced Materials for Extreme Environments

Although advanced materials for extreme environments were originally investigated for applications in the aerospace industry, they have also generated interest in other sectors. BCC Research has actually identified three key sectors in which these materials are used:

- Aerospace and defense.
- Energy.
- Mechanical/chemical/metallurgical.
- Others.

A more detailed discussion of these applications follows.

Aerospace and Defense

Aerospace and defense is the most traditional field of application for advanced materials for extreme environments. These materials are not only being developed for creating various components of atmospheric re-entry vehicles and hypersonic planes, but they are also used to produce low-ablation thermal protection systems, propulsion system components, parts for advanced weapons, armors, and microwave absorbing materials.

A summary of applications of advanced materials for extreme environments in aerospace and defense is provided in the table below.

Table 5
Applications of Advanced Materials for Extreme Environments in Aerospace and Defense, 2020

Applications
Aerospace components
Atmospheric re-entry vehicles
Hypersonic vehicles
Wing leading edges
Propulsion system components
Thermal and environmental barriers
Weapons
Microwave absorbing materials for high-temperature environments
Armors

Source: BCC Research

Energy

Within the energy sector, advanced materials for extreme environments find application in the fabrication of gas turbine components, parts for heat exchangers, nuclear reactors and solid oxide fuel cells, as well as other components used in solar energy, batteries, and thermoelectric generation.

Nuclear energy represents one of the most important fields of application for advanced materials for extreme environments. Recently, UHTCs, and in particular niobium carbide, have been introduced in the manufacturing of cladding for nuclear fuels consisting of fissionable microspheres of uranium oxide.

There is also increasing interest in propulsion systems for deep-space missions based on nuclear reactors. These propulsion systems utilize the thermal energy created in the nuclear reactors to heat hydrogen at temperatures above 1700°C. Advanced materials for extreme environments are used to produce various components for both the reactor and the propulsion system.

A summary of typical applications of advanced materials for extreme environments in the energy sector is provided in the table below.

Table 6
Applications of Advanced Materials for Extreme Environments in the Energy Sector, 2020

Applications
Gas turbine components for fossil energy power production
Components for heat exchangers
Fuel encapsulation for nuclear reactors
Non-oxide fuels
Components for new generations of nuclear reactors
Neutron absorbers in nuclear plants
Parts for solid oxide fuel cells
Solar energy absorbers for concentrated solar power plants
Heat-shielding structures for the oil and gas industry
Battery components
Thermoelectric generators

Source: BCC Research

Mechanical/Chemical/Metallurgical

In the mechanical/chemical/metallurgical sector, advanced materials for extreme environments are of interest primarily for their high hardness, corrosion resistance, chemical stability and high-temperature resistance.

Sputtering targets have become very popular for production of durable thin film coatings. Wear-resistant components, including cutting tools, benefit from the elevated hardness of these materials, whereas the stability advanced materials for extreme environments at very high temperature is exploited for production of thermocouple tubes, pipes for transport of hot fluids, and high-temperature protection shields. Corrosion resistance and chemical stability are of advantage in the fabrication of catalysts, plasma arc electrodes, and parts subjected to highly oxidative and corrosive conditions.

All these applications are summarized in the next table.

Table 7
Applications of Advanced Materials for Extreme Environments in the Mechanical/Chemical/Metallurgical Sector, 2020

Applications
Cutting tools
Wear-resistant components
Micro drills
Holding fixtures for cutting tools
Sputtering targets for hard material coatings
Evaporation boats
Furnace elements
Crucibles for non-ferrous metals
High-temperature protection shielding
Thermocouple tubes
Pipes for transport of high temperature fluids
Molten metal handling
Cathode material for aluminum smelting flux electrolysis
Plasma arc electrodes
Components for highly oxidative and corrosive conditions
Catalysts

Source: BCC Research

Others

As shown in the table below, advanced materials for extreme environments also find application in the medical and electronics sectors. Recently, biocompatible coatings with improved tribological properties have been manufactured using high-entropy carbides, a new class of materials characterized by very high hardness.

In addition, advanced materials for extreme environments have generated growing attention as high-temperature microwave absorbing materials and supercapacitors for electronic applications.

Table 8
Applications of Advanced Materials for Extreme Environments in Other Sectors, 2020

Applications
Biocompatible materials
Microwave absorbing materials for high-temperature environments for electronics
Supercapacitors

Source: BCC Research

Chapter 4

Technology

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Chapter 4: Technology

Introduction

This chapter provides an updated review of materials, properties and production methods of advanced materials for extreme environments.

Key technological changes and innovations that have occurred in recent years are also outlined, with a particular focus on emerging materials and technologies that are expected to have a significant impact on industry growth during the next five to ten years.

Also provided is an overview of organizations that are involved in the research and development of advanced materials for extreme environments, with a brief summary of their main activities.

Materials

The three most important classes of advanced materials for extreme environments are ultrahigh temperature ceramics (UHTCs), high-entropy ceramics (HECs), and MAX phases.

These ceramics are achieving increasing interest primarily for their resistance to ultrahigh temperature, harmful radiations, elevated stresses, as well as oxidative and corrosive conditions.

Ultrahigh Temperature Ceramics

Ultrahigh temperature ceramics are typically defined as materials with melting point equal or greater than 3000°C. They are suitable for applications above 2000°C for short times (no more than a few hours).

There are only 18 elements and compounds that satisfy this requirement. They are listed in the table below. By comparison, there are many more materials with melting temperature greater than 2000°C, accounted to be over 300 and including, in addition to the 18 listed below, various refractory metals (e.g., hafnium, niobium, and iridium), oxides (e.g., zirconia and hafnia), carbides (e.g., silicon carbide), boride, nitrides, and other compounds.

Table 9
Ultrahigh Temperature Materials

Main Category	Material	Melting Point (°C)
Elements	Carbon	3,550
	Tungsten	3,422
	Rhenium	3,185
	Tantalum	3,017
Borides	HfB_2	3,250
	ZrB_2	3,246
	TiB_2	3,230
	TaB_2	3,140
	NbB_2	3,050
Carbides	HfC	3,900
	TaC	3,880
	ZrC	3,532
	NbC	3,490
	TiC	3,160
Nitrides	HfN	3,305
	TaN	3,090
	BN	3,000
Oxides	ThO_2	3,390

Source: BCC Research

High temperature resistance is a very important property of UHTCs, but there are other characteristics that are requested from these materials, including oxidation resistance and chemical stability at very high temperatures, high mechanical strength, superior hardness, low thermal expansion, high thermal shock resistance, high thermal conductivity, high density, easy manufacturability and low fabrication costs.

These properties are not only needed in demanding applications within the aerospace and defense sector(e.g., hypersonic jets, rockets, and re-entry vehicles), but they are also being exploited in other fields such as in the manufacturing of parts for high temperature furnaces, metal melting systems, wear-resistant devices, and new generations of nuclear reactors.

However, not all of the above materials provide all the properties desired for these uses. For example, oxides typically show low thermal shock resistance, whereas carbon burns above 800°C in air, even though it exhibits a very high theoretical melting point.

As a result, over time, borides, carbides and nitrides containing group IV and V elements (e.g., ZrB_2, HfB_2, HfC, TaC, and HfN) have become the most popular UHTCs.

Borides
Borides are characterized by very high hardness and temperature resistance as well as high thermal conductivity, making them suitable for very high temperature applications (above 2000°C), such as in rocket nozzles. Their peculiar properties are due to their hexagonal crystal structure comprising two-dimensional boron layers, similar to graphene, which alternate with hexagonally close-packed metal layers, featuring strong B-B and M-B bonds.

However, borides are generally difficult to sinter and exhibit moderate fracture toughness, which has prevented their widespread use.

Transition metal diborides represent the most important type of UHTCs, having characteristics superior to monoborides. The most common diborides are HfB_2 and ZrB_2, which exhibit hardness of 28 GPa and 23 GPa, respectively, the highest among the borides. Additionally, HfB_2 has high thermal and electrical conductivity, low coefficient of thermal expansion and good thermal shock resistance. It maintains good mechanical properties at temperatures up to 2200°C and exhibits an oxidation resistance 10 times that of zirconium diboride.

Zirconium diboride has high mechanical strength, hardness, electrical and thermal conductivities, but is characterized by a long fabrication process and is difficult to machine into precise structures.

Carbides
Carbides are another group of important materials. The most popular are hafnium carbide and tantalum carbide, which exhibit the highest melting points among all UHTCs, at 3900°C and 3880°C, respectively. These materials are also characterized by high hardness and elastic modulus, as well as high-temperature ablation resistance.

Carbides are less common than borides due to their low-temperature, which consists in the formation of oxide grains at temperatures below 1500°C. These oxide grains do not sinter but separate from the carbide structure. Carbides are generally more difficult to process than borides.

Nitrides
Similar to transition metal carbides, nitrides behave like metals, with high electrical and thermal conductivities as well as catalytic behavior. However, when exposed to very high temperatures for a long time, nitrides tend to lose nitrogen atoms and their properties degrade.

Composites
The main drawbacks of borides, carbides and nitrides are their low fracture toughness, inadequate oxidation resistance at very high temperatures (above 1100°C they form a porous and weak oxide), and difficulty in manufacturing, including poor sinterability. Poor sinterability is due primarily to their very high melting point and low self-diffusion coefficient. These materials typically need to be sintered at temperatures greater than 2000°C and under pressure (30 MPa to 100 MPa), which leads to formation of large grains and a porous microstructure, resulting in a degradation of their thermo-mechanical properties. Improvements have been achieved by the fabrication of ceramic matrix composites (CMCs).

The next table provides a summary of CMC compositions for ultrahigh temperatures that have been introduced to date (as previously mentioned the first material is the secondary phase; in ternary or quaternary systems, the volume fraction of each component increases from left to right). These materials are primarily based on borides and carbides as the matrix material with silicon-based materials (e.g., SiC, $TaSi_2$ and $MoSi_2$) and carbon as the secondary phase.

SiC/ZrB_2-based CMCs have become a very popular category of ultrahigh temperature CMCs. They are also the most studied among all diboride composites. Silicon-based materials (typically added at a volume fraction between 15% and 20%) have long been known to enhance the boride oxidation resistance at high temperatures by forming a borosilicate glass on the surface of these materials, which prevents further diffusion of oxygen in the bulk material thus acting as an environmental barrier. Other improvements in oxidation resistance can be achieved with additions of tungsten, molybdenum and niobium, which have been found to reduce the evaporation rate of surface glass.

SiC and silicides also increase sinterability by promoting liquid phase sintering through the formation of a liquid borosilicate phase.

Carbon, instead, has been found to further improve thermal shock resistance. Higher fracture toughness and thermal shock resistance have been achieved in SiC/ZrB_2 by using aluminum, boron carbide and carbon as sintering additives. Ceramics with this composition sintered at 1800°C by spark plasma sintering exhibited a fracture toughness of 6.15 MPa $\cdot$ $m^{1/2}$. By comparison, the fracture toughness of traditional ZrB_2 ceramics is in the range 3-4 MPa $\cdot$ $m^{1/2}$, whereas SiC typically reaches 5 MPa $\cdot m^{1/2}$.

Another study has demonstrated that aluminum by itself can rise fracture toughness. By adding 2.5% aluminum by weight to SiC/ZrB_2, a ceramic with density of 99.8% of theoretical and fracture toughness of 6.3 MPa $\cdot$ $m^{1/2}$ can be obtained using spark plasma sintering at 1900°C and 40 MPa.

Recently, zirconium and hafnium borides with SiC and Y_2O_3 have been developed, which exhibit good oxidation resistance at temperatures as high as 2200°C.

Among the carbides, TaC reinforced with SiC and carbon (for example, carbon nanotubes) is the most common. This material exhibits enhanced oxidation resistance, smaller grain size, and enhanced toughness compared with conventional TaC.

TaC mixed with 10% by weight of TaB_2 can be sintered by hot pressing at lower temperature than monolithic TaC while achieving improvements in hardness, Young's modulus and oxidation resistance.

Recently, composites based on TaC and group IV compounds (i.e., materials containing Hf, Zr and Ti) have been gaining increasing attention for their high melting temperature and because they form stable high-melting temperature oxides. These materials are suitable for oxidizing conditions and rapid heating at temperature greater than 1600°C.

Self-healing Ceramics

SiC and carbon fibers or whiskers, in place of particles or platelets, are becoming more common as a secondary phase in UHTCs such as zirconium diboride, hafnium diboride and tantalum carbide to improve their thermal shock resistance and damage tolerance.

Discontinuously and continuously reinforced ultrahigh temperature ceramic matrix composites containing carbon and SiC fibers or whiskers have been found to confer self-healing properties to the matrix material. Self-healing means that cracks forming in the ceramic can be at least partially sealed through a thermal treatment. Self-healing, which can also be enhanced by doping the composite with tungsten carbide, is achieved by the formation of oxidation products such as zirconium oxide and boron oxide liquid phases that are able to reach the flaw and fill it.

Recently, scientists have been able to grow *in situ* SiC whiskers in SiC/ZrC/ZrB_2 ceramics using a pyrolysis process with an iron catalyst.

Table 10
Ceramic Matrix Composites for Ultrahigh Temperatures

Matrix Material	CMC Systems
Zirconium diboride	SiC/ZrB_2
	$MoSi_2$/ZrB_2
	$ZrSi_2$/ZrB_2
	C/ZrB_2
	Carbon nanotubes/ZrB_2
	ZrC/ZrB_2
	LaB_6/ZrB_2
	C/SiC/ZrB_2
	B/SiC/ZrB_2
	B_4C/SiC/ZrB_2
	La_2O_3/SiC/ZrB_2
	Si_3N_4/SiC/ZrB_2
	$TaSi_2$/SiC/ZrB_2
	WC/ZrC/ZrB_2
	AlN/SiC/ZrB_2
	ZrC/SiC/ZrB_2
	B_4C/C/SiC/ZrB_2
	Y_2O_3/SiC/ZrB_2
Hafnium diboride	C/HfB_2
	SiC/HfB_2
	$MoSi_2$/HfB_2
	$ZrSi_2$/HfB_2
	C/SiC/HfB_2
	$TaSi_2$/SiC/HfB_2
	SiC/ZrB_2/HfB_2
	C/SiC/HfC/HfB_2
	Y2O_3/SiC/HfB_2

Matrix Material	CMC Systems
Titanium diboride	SiC/TiB_2
	ZrC/TiB_2
	TiC/TiB_2
	B_4C/TiB_2
	$MoSi_2/TiB_2$
	AlN/TiB_2
	Si_3N_4/TiB_2
Tantalum diboride	$MoSi_2/TaB_2$
Carbides	$C/SiC/TaC$
	SiC/ZrC
	TaB_2/TaC

Source: BCC Research

Nanoporous Ceramics
In recent years, new mechanisms for toughening ceramics have been investigated, such as nanoporosity. Nanoporosity has been found to provide quasi-ductile behavior in ceramics. Tunable nanoporous materials with uniformly distributed nanoporosity have been obtained by spark plasma sintering.

As shown in the table below, the introduction of materials with improved properties is contributing to increase the number of applications for UHTC monoliths, conventional composites, and self-healing ceramics in various sectors.

Table 11
Typical Applications of UHTCs, 2020

Sector	Applications
Aerospace and defense	Hypersonic vehicles
	Atmospheric re-entry vehicles
	Aerospace components
	Weapons
	Wing leading edges
	Propulsion system components
	Thermal and environmental barriers
	Microwave absorbing materials in high-temperature environments for aerospace applications
	Armors
Energy	Fuel encapsulation for nuclear reactors
	Non-oxide fuels
	Components for new generations of nuclear reactors
	Gas turbine components for fossil energy power production
	Components for heat exchangers
	Heat-shielding structures for the oil and gas industry

Sector	Applications
	Solar energy absorbers for concentrated solar power plants
	Neutron absorbers in nuclear plants
Mechanical/chemical/metallurgical	Sputtering targets for hard material coatings
	Evaporator boats
	Wear-resistant components
	Cutting tools
	Micro drills
	Pipes for transport of high temperature fluids
	Molten metal handling
	Cathode material for aluminum smelting flux electrolysis
	Furnace elements
	Crucibles for non-ferrous metals
	High-temperature protection shielding
	Thermocouple tubes
	Plasma arc electrodes
	Components for highly oxidative and corrosive conditions
Others	Biocompatible materials
	Microwave absorbing materials for high-temperature environments for electronics

Source: BCC Research

High-Entropy Ceramics

Lately, a new category of materials suitable for extreme environments applications has been introduced: high-entropy ceramics (HECs). HECs are multicomponent, equimolar compounds obtained from solid solutions of materials with the same crystal structure.

High-entropy ceramics are typically characterized by high melting point, good thermal stability, low thermal and electrical conductivity, high hardness, high mechanical strength and good corrosion resistance. HECs generally exhibit better properties when compared with diborides or carbides of single metals, due to the presence of atoms of different dimensions and types that affect the distribution of defects and dislocations as well as the movement of diffusing species.

In particular, electrons and phonons are scattered in these materials; consequently, HECs have much lower thermal conductivity than monoborides and monocarbides. For example, $(Hf_{0.2}Zr_{0.2}Ta_{0.2}Nb_{0.2}Ti_{0.2})C$ has a thermal conductivity of 6.4 W/mK versus a thermal conductivity of approximately 30 W/mK of ZrC and HfC. Thus, HECs represent a new group of insulating materials. Their thermal insulation can be further decreased by fabricating porous structures.

In addition, by substituting hafnium with molybdenum in the above high-entropy carbide composition, finer grain size and high density close to 99.0% of theoretical have been achieved, as well as nanohardness greater than what measured in other high-entropy carbides.

Scientists at the University of California in San Diego have recently developed high-entropy non-oxide materials based on borides of the type $(Hf_{0.2}Zr_{0.2}Ta_{0.2}Nb_{0.2}Ti_{0.2})B_2$ characterized by one solid-solution boride phase with hexagonal AlB_2 structure. They were produced by mixing five commercial metal diboride powders using ball milling for six hours, followed by compaction and densification at 2000°C and 30 MPa for 5 minutes by spark plasma sintering. These materials feature higher hardness and oxidation resistance than conventional single metal diborides manufactured with the same process.

HECs with density of 99% of theoretical and above have also been fabricated by introducing a rapid process based on reactive flash spark plasma sintering.

High-entropy carbides with density up to 99.3% of theoretical have been manufactured by mixing oxides by high-energy ball milling followed by carbothermal reduction and hot pressing at 1900°C. Lately, scientists have reported that the fracture toughness and bending strength of high-entropy carbides can be further improved by adding 20% SiC by volume. This CMC is fabricated by spark plasma sintering.

HECs are finding application in the aerospace, mechanical/chemical/metallurgical and energy sectors, as indicated in the next table.

Table 12
Typical Applications of High-Entropy Ceramics, 2020

Sector	Applications
Aerospace and defense	Thermal and environmental barrier coatings
Energy	Battery components
	Thermoelectric generators
Mechanical/chemical/metallurgical	Wear- and corrosion-resistant components
	Catalysts
Others	Supercapacitors

Source: BCC Research

MAX Phases

MAX phases are ternary systems characterized by a hexagonal layered structure. M indicates a transition metal, such as titanium, chromium, zirconium, niobium, hafnium, or tantalum; A is a III A or IVA group element (e.g., aluminum, silicon, phosphorus, gallium, germanium, cadmium, and tin); and X indicates a carbide or nitride.

MAX phases combine some of the most desirable properties of ceramics and metals, such as high fracture toughness, high thermal shock resistance, excellent wear and oxidation resistance, ultra-low friction, and high thermal and electrical conductivity. The most common MAX phases consist of carbides (Ti_3SiC_2, Ti_3AlC_2, Ti_2AlC, Nb_4AlC_3 and Nb_2AlC) and nitrides (Ti_4AlN_3). Although most MAX phases do not have the ultrahigh melting points of traditional ultrahigh temperature ceramics, they are of interest for many applications in harsh environments, including for fabrication of components for gas turbines and nuclear reactors as well as parts for aerospace and very high temperature conditions, as shown in the next table.

Table 13
Typical Applications of MAX Phases, 2020

Sector	Applications
Aerospace and defense	Aircraft engine components
Energy	Components for gas turbines
	Components for nuclear reactors
	Nuclear fuel cladding
	Parts for solid oxide fuel cells
Mechanical/chemical/metallurgical	Holding fixtures for cutting tools
	Components for furnaces

Source: BCC Research

Basic Fabrication Process of Advanced Materials for Extreme Environments

Fabrication processes for advanced materials for extreme environments can be divided according to two main groups: monoliths and composites. As previously defined, the term monoliths in this study refers to ceramics made from one type of materials (either pure or a solid solution), whereas composites contain two or more materials.

Monoliths

Monolithic components of advanced materials for extreme environments consist primarily of traditional UHTCs, such as borides, carbides and nitrides. Fabrication of this monolithic ceramics starts from powders. Boride and carbide powders are typically produced by carbothermal reduction of oxides, using carbon and boron as reducing agents. For example, zirconium diboride powder is obtained from zirconium oxide (ZrO_2)and boron oxide (B_2O_3) in presence of carbon. Carbothermal reduction to obtain ZrB_2 occurs at temperatures of approximately 2000°C and with excess boron oxide to prevent carbide formation.

Another common process for producing boride and carbide powders is self-propagating high-temperature synthesis (SHS) from pure elements, also known as combustion synthesis. In this process, a mix of pure elements, for example boron and zirconium, are placed in a crucible in contact with ignition electrodes. The reaction chamber is sealed and air is removed; then, an inert gas, such as argon, is injected in the chamber. Electric pulses are applied to the electrodes to begin a combustion reaction that leads to the formation of the desired material. Researchers have found that SHS can be an effective method for preparing high-entropy ceramic compositions in place of the more time-consuming ball milling step.

Nitride powders are instead normally synthesized by direct nitridation, consisting of high-energy milling of metal particles (e.g., hafnium) under nitrogen atmosphere.

To fabricated parts from these powders, the standard process consists of uniaxial hot-pressing or hot isostatic pressing in graphite molds at high temperatures, typically above 1600°C. Recently, spark plasma sintering (SPS) has been introduced in the fabrication of the components of advanced materials for extreme environments, both monolithic and composite.

Spark Plasma Sintering

Spark plasma sintering (SPS), which is also known with a variety of other names such as pulsed electric current sintering (PECS), rapid hot pressing (RHP), current activated pressure-assisted densification (CAPAD), electric pulse assisted consolidation (EPAC), field-assisted sintering technique (FAST), pressure plasma consolidation (P2C), and direct current sintering (DCS), is a process designed to quickly reach very high temperatures (up to 2400°C).

Thermal energy is provided, rather than by external heating as in hot pressing, by a high-density current flux that flows through the material. Heating and cooling occur at rates of 300°C/min or faster, allowing for short sintering times. Usually, parts can be sintered at temperatures that are 200°C to 500°C lower than in conventional sintering.

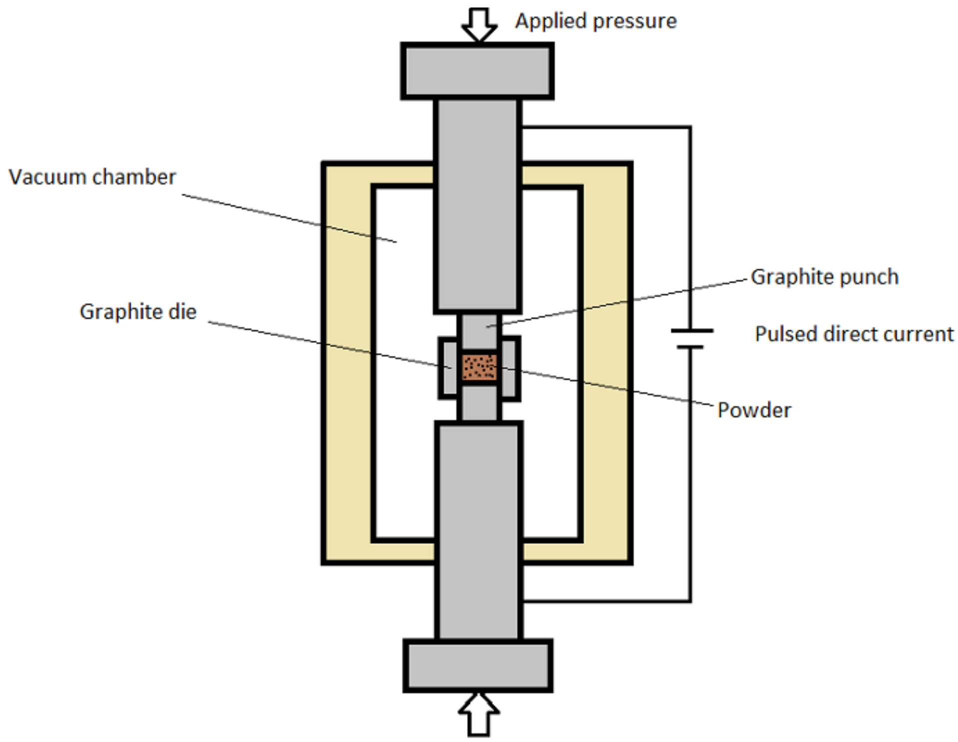
A diagram of a typical SPS system is provided in the figure below. The furnace entails two graphite punches that also act as electrodes, a graphite die placed in between, a direct current pulse generator, and a controller for controlling the pulse current generator and the pressing assembly. One or both of the electrodes move unidirectionally to compress the powder or a previously formed compact placed in the die.

The current generator is switched on to provide electricity to the conductive mold so that plasma is generated. Pulses typically last between 1 millisecond and 300 millisecond and range between 500 A (A= ampere) and 8,000 A, at low DC voltages, usually less than 10 Volts. The current is usually applied for less than 20 minutes, under applied pressures generally less than 100 MPa. The pressing chamber operates under vacuum (3 Pa to 8 Pa) or may be filled with an inert gas.

The plasma that forms typically contains reactive species such as hydrogen atoms, protons, methyl and carbon groups, or metal ions. These species activate the particle surface which, together with localized surface heating, leads to the formation of bonds (or necks) between particles. Joule heating generated by the electrical current flowing through the connected particles causes diffusion of materials toward the necks promoting sintering.

Due to the high temperature the particles become softer and the applied pressure further enhances sintering through a mechanism of plastic deformation. Because of the rapid consolidation, minimal grain growth occurs. In large samples, pressure is commonly increased gradually to promote outgassing at low temperature and diffusion at higher temperatures.

Figure 5
Basic Configuration of a Spark Plasma Sintering System



Source: BCC Research

This process is particularly well suited for achieving fully dense products (i.e., close to 100% of theoretical density) and for sintering fine-grained materials at low temperatures, in particular from high-melting point materials, as well as for preventing the formation of undesired phases.

SPS, which can be applied in the processing of both conductive and nonconductive materials, is becoming quite popular for the development of technical ceramics and alloys that cannot be produced otherwise or that are difficult to sinter, such as UHTCs.

Other advantages of SPS, which are useful in the manufacture of advanced materials for extreme environments, include:

- it can be used to process powders that do not have a binder, eliminating the need for a binder burnout step;
- it minimizes internal stresses and microcracks generated by uneven heat distribution through the workpiece;
- it is particularly well-suited for the densification of nanocomposites, since it prevents grain growth during sintering;
- components fabricated by SPS exhibit improved mechanical properties;
- generally speaking, parts with fewer microstructural defects are produced by SPS;
- it can be applied to both oxide and non-oxide materials and composites;
- without the need of a binder, net or near-net shapes are possible for many parts with simple configuration;
- the equipment can be easily integrated with automation and robotic systems;
- due to its high speed, it reduces operational expenses.

Spark plasma sintering has become a very important process for fabrication of UHTCs and ultrahigh temperature CMCs. It allows to achieve better control of temperature distribution during sintering resulting in higher density, more uniform microstructure and improved properties of the sintered components. Fine-grained UHTC components have been obtained by high-pressure spark plasma sintering with pressure of 250 MPa.

Recently, scientists have found that SPS can be used to achieve solid-state reactions aimed at obtaining specific compounds. This process is called reactive spark plasma sintering. It is being applied in the development of two phase high-entropy boride-carbide ceramics.

The next table provides the basic fabrication steps used in the manufacture of monolithic components of advanced materials for extreme environments.

Table 14
Basic Steps in the Fabrication of the Monolithic Components of Advanced Materials for Extreme Environments

Step	Method
Powder preparation	Carbothermal reduction (borides and carbides)
	Self-propagating high-temperature synthesis (borides and carbides)
	Direct nitridation (nitrides)
Powder forming and sintering	Hot pressing
	Hot isostatic pressing
	Spark plasma sintering

Source: BCC Research

Composites

Advanced composite materials for extreme environments consist primarily of CMCs. They can be produced as discontinuously reinforced composites (DRCs) or continuously reinforced composites (CRCs), also known as continuous fiber ceramic composites (CFCCs).

Discontinuously Reinforced Composites

In DRCs, the reinforcing phase is added to the matrix in the form of particles, platelets, whiskers, or chopped fibers.

Particles represent the most traditional type of reinforcing phase for CMCs and can be made of various materials including metals and pure elements, carbon, oxides and non-oxides.

Platelets are ceramic structures with a typical diameter between 10 and 100 microns, and a thickness between 1 and 10 microns. They increase fracture toughness but tend to decrease flexural strength compared to the base material. Silicon carbide and zirconium boride are the most common platelet types used for the DRCs of advanced materials for extreme environments.

Whiskers are rod or needle-shaped, single-crystal structures characterized by a diameter below 10 microns and a high aspect ratio (the ratio between length and diameter), typically greater than 10. Whiskers are characterized by high tensile strength (up to 16 GPa), high Young's modulus (approximately 600 GPa for SiC whiskers) and high-temperature stability (SiC whiskers are stable up to 1800°C). Although whiskers are very effective in increasing ceramic fracture toughness, their use is limited due to health concerns. SiC whiskers, however, are receiving increasing interest in the fabrication of DRCs of advanced materials for extreme environments.

Chopped fibers have a polycrystalline structure and are obtained by cutting to size fibers produced with technologies similar to those used to manufacture commercial polymeric fibers such as nylon and polyester. Chopped fibers are characterized by a larger diameter (up to 20 microns) and lower temperature resistance compared to whiskers (for example, SiC fibers withstand temperatures up to 1200°C). Carbon and carbide fibers (e.g., silicon carbide, TaC, and ZrC) are becoming more popular in the fabrication of advanced DRC materials for extreme environments.

Advanced DRC materials for extreme environments are typically produced by conventional ceramic powder processing in which the matrix material and the secondary phase[s] are combined together by mixing and/or milling, followed by forming and sintering using hot pressing, hot isostatic pressing or spark plasma sintering.

Continuously Reinforced Composites

Advanced CRC materials for extreme environments are prepared by various techniques, the most common of which are melt infiltration (MI), polymer infiltration and pyrolysis (PIP), slurry infiltration (SI), and chemical vapor infiltration (CVI).

All these processes start with a fibrous material, which will become the secondary phase, after being infiltrated (or impregnated) with a fluid (the matrix material). The fibrous material can be made of filaments or yarns, or it can be a preform. The filaments or yarns are combined with the fluid by either a mixing process or by dipping in the fluid.

The preform, instead, is fabricated using long filaments mixed with an organic resin. The mixture is placed in a mold and heated under pressure to obtain the desired shape. Next, the resin is decomposed by pyrolysis, obtaining a porous structure that can be infiltrated with the matrix-forming fluid.

Melt Infiltration

Melt infiltration (MI) is a pressureless process in which the infiltration fluid is a molten metal. The process starts with solid metal placed on top of a fibrous compact. Upon heating, the metal melts and penetrates the fibrous material by capillary action. By sintering under nitrogen atmosphere, nitride matrices can be manufactured. Very dense composites can be produced by MI.

This process is typically used for fabrication of carbide and nitride advanced composite materials for extreme environments reinforced with carbon, silicon carbide, and silicon nitride.

Polymer Infiltration and Pyrolysis

Polymer infiltration/pyrolysis (PIP) utilizes a polymer-derived ceramic resin (also known as pre-ceramic resin) for impregnation. After infiltration, the material is formed to the desired shape and cured to polymerize the resin typically in autoclave or by hot pressing. Then the compact is subjected to a high-temperature heating treatment to remove the resin and obtain a ceramic compact.

Slurry Infiltration

Slurry infiltration (SI) is under many aspects similar to PIP, the major difference being that the fibrous material is infiltrated with a ceramic slurry. The ceramic slurry is a mixture of ceramic powder, binder and solvent. After infiltration, the fibrous material is dried and molded by hot pressing producing a green compact that is subjected to a binder burn-out and sintering process.

Slurry infiltration is gaining increasing popularity for fabrication of ultrahigh-temperature CRCs. In recent years, new matrix materials have been developed by combining traditional ceramic slurries or ceramic precursors with silicon-based preceramic polymers. For example, polycarbosilane has been mixed with a zirconium-based polymer to prepare an impregnation fluid suitable for producing a ZrC-SiC matrix.

Chemical Vapor Infiltration
In chemical vapor infiltration (CVI), the fibrous material (a flexible fabric or a rigid preform) is infiltrated with precursor vapors, instead of a liquid as in the other methods previously described. By precisely controlling the reactor temperature and pressure, the precursor is decomposed and deposited as a solid element or compound within the pores of the preform.

CVI permits to manufacture composites with complex shapes and different sizes, and with a variety of matrix materials, but the process is characterized by long production times, low precursor conversion efficiency, and high manufacturing costs. As a result, CVI is not used in high volume manufacturing.

Other Steps
After impregnation, all of these processes have in common that the workpiece is dried and then subjected to a pyrolysis/binder burnout step to remove the volatile components, leaving a porous structure. Multiple steps of impregnation followed by pyrolysis are usually performed to achieve high density materials.

Forming by compression may occur at different stages of the fabrication process, depending on the particular case.

The final step is sintering which is usually achieved by hot pressing, HIP, or spark plasma sintering. In some cases, forming and sintering are combined in one step.

The basic fabrication process for advanced composite material components for extreme environments is summarized in the next table. The sequence of these steps may vary.

Table 15
Basic Steps in the Fabrication of the Components of Advanced Composite Materials for Extreme Environments

Composite Type	Step
Discontinuously reinforced ceramics	Particles, platelets, whiskers or chopped fibers are combined with the matrix material by mixing and/or milling
	Binder addition
	Spray-drying
	Forming and sintering are performed by hot pressing, hot isostatic pressing or spark plasma sintering
Continuously reinforced composites	A fibrous material is impregnated by melt infiltration, polymer infiltration and pyrolysis, slurry infiltration, or chemical vapor infiltration
	Drying
	Forming is performed by cold pressing, hot pressing or hot isostatic pressing
	The impregnated fibrous materials are pyrolyzed
	Impregnation is repeated several times
	Sintering is performed by hot pressing, hot isostatic pressing or spark plasma sintering

Source: BCC Research

Laminar Composites

Laminar composites are much less popular than CMCs for the manufacture of advanced materials for extreme environments. They are commonly produced using a sequence of steps consisting of tape casting to form ceramic sheets, lamination (the sheets are compacted together by hot pressing), binder burn-out, mechanical shaping, and sintering. Recently, laminates consisting of layers of graphite and SiC/ZrB_2 were fabricated by tape casting and hot pressing. These laminates exhibit improved fracture toughness and flexural strength.

Emerging Fabrication Processes

In addition to the basic fabrication methods previously described there are other processes that have been receiving growing attention in recent years for the fabrication of advanced materials for extreme environments.

Polymer-Derived Ceramics

Although polymer-derived ceramics have been known for more than three decades, the level of research activities related to this technology has surged in recent years, especially with regards to the fabrication of advanced ceramic matrix composites, such as advanced composite materials for extreme environments.

Polymer-derived ceramics (PDCs) are obtained from polymer precursors, also known as preceramic polymers because they contain organic-inorganic groups. When heated at high temperatures (typically greater than 800°C) the organic component undergoes pyrolysis, while the inorganic component is converted from an amorphous to a crystalline solid, forming a ceramic.

A variety of polymer precursors have been introduced to date for PDC fabrication, some of the most common being polysiloxane, polycarbosilane, polyborosiloxane, polyborosilane, polyborosilazane, poly(vinyl)silazane, polycarbosiloxane, polysilazane, polysilylcarbodiimides, as well as metallorganic compounds and special resins. Polymer precursors can be blended with various types of fillers, continuous or discontinuous, to form CMCs.

Research related to PDCs has increased more rapidly in recent years for a number of reasons, including:

- There is a need to produce high-temperature ceramics with low cost processes. Both UHTCs monoliths and composites are being manufactured based on preceramic polymers. For example, SiC/ZrB_2 has been prepared from a preceramic mixture containing zirconium silicate, boron carbide and a phenolic resin in ethanol, followed by pyrolysis at 1650°C in argon atmosphere. Instead, the ZrC/ZrB_2 has been produced from borane and a zircon-based metallorganic precursor.

- PDCs are fabricated at temperatures between 500°C and 1000°C lower than with conventional ceramic processes, resulting in relevant energy savings.

- Very pure materials with fine microstructure at the nanoscale can be produced by the PDC route.

- PDCs often exhibit improved thermo-mechanical properties over similar materials obtained by other processes.

- PDCs can be fabricated into complex shapes by using well-known polymer forming technologies such as injection molding, extrusion, and polymer infiltration and pyrolysis (PIP).

- PDCs offer considerable potential for being applied in additive manufacturing.

Recently, nanostructured Ta_4HfC_5 has been produced from polymers based on tantalum and hafnium alkoxides mixed with a phenolic resin that acts as the carbon source. After pyrolysis of the polymer precursors, nanoparticles of Ta_4HfC_5 were obtained, suitable for fabrication of ceramic components by spark plasma sintering. Ta_4HfC_5, which is a 4 to 1 ratio compound of TaC and HfC, has a very high melting point (4215 K or 3942°C), the highest among all the UHTCs known to present.

SiC/TaC nanocomposites have also been prepared from a precursor obtained by blending polycarbosilane and polytantaloxane, followed by pyrolysis in argon atmosphere.

Scientists at the Indian Space Research Organization (Kerala, India) have developed an innovative preceramic precursor containing zirconium, titanium, boron and silicon called zirconotitanoborosiloxane, prepared by non-aqueous sol–gel process. The material is capable of sintering at 1500°C and can form non-oxide ceramics by carbothermic and borothermic reductions.

Additive Manufacturing

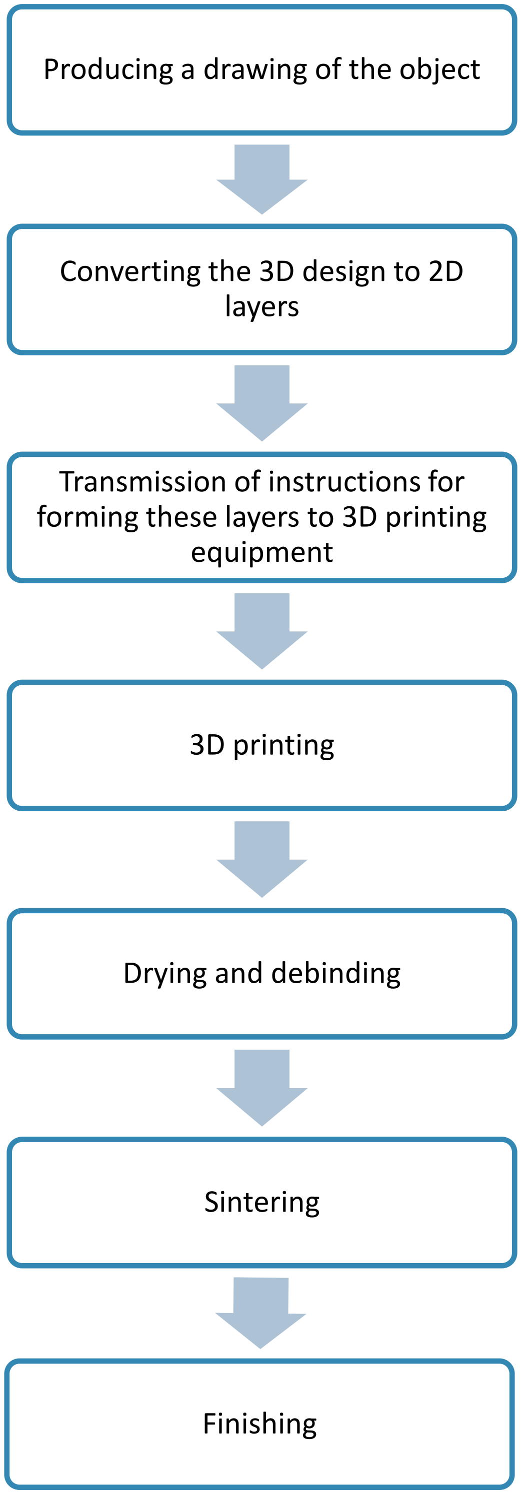
Additive manufacturing (AM), which is also known as 3D printing (3DP), solid-free form fabrication (SFF) and rapid prototyping (RP), is a process that produces structures layer by layer. 3D printing has had enormous growth in recent years and is being applied in different industry sectors such as biomedical, aerospace, and industrial manufacturing. It has been gaining increasing interest also for fabrication of technical ceramics, including components for extreme environments. Additive manufacturing offers the advantages of design flexibility, capability to manufacture parts with complex configuration, reduced production costs, and shorter manufacturing time.

As shown in the figure below, the first step in the fabrication of technical ceramics by 3D printing consists of producing a drawing of the object with the aid of computer-aided design (CAD) software. Other less common techniques are based on mathematical equations or topological optimization.

The drawing is then transformed into two-dimensional (2D) slices (i.e., cross-sections) or layers, and instructions for manufacturing these layers are transmitted to the equipment that builds the object, typically using computer-aided manufacturing (CAM) software.

Next, the workpiece is 3D printed. Several processes have been developed or are under development for the fabrication of technical ceramics, which are detailed in the following sections. After 3D printing, the object is dried and then sent through binder burn-out (or debinding) and sintering. Finally, a finishing step provides the workpiece with the surface characteristics required by the particular application.

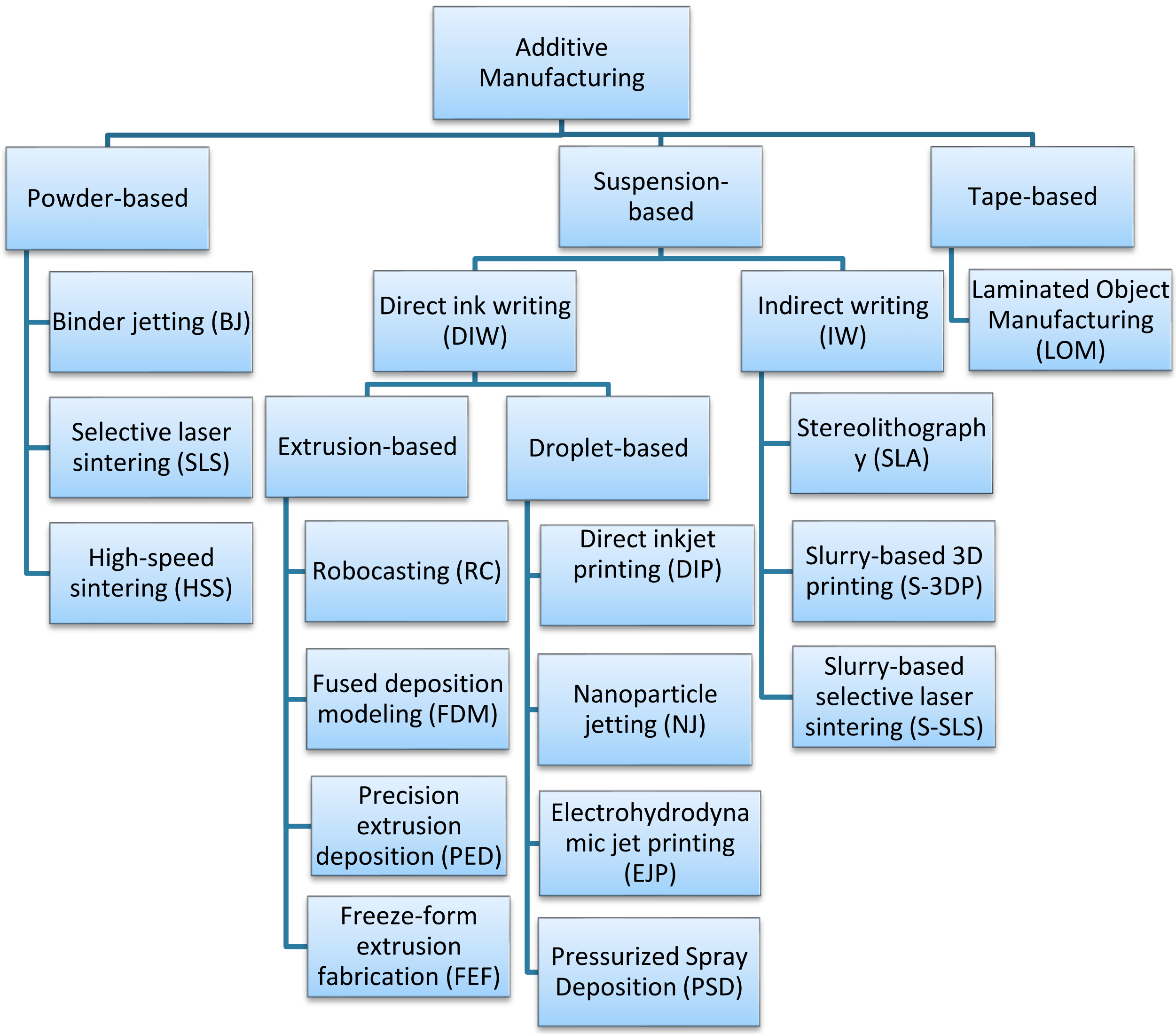
Figure 6
Basic Steps in the Fabrication of 3D Printed Technical Ceramics



Source: BCC Research

The next figure summarizes various processes that have been applied to the fabrication of technical ceramics. Based on the type of materials used, 3D printing processes are classified in: powder-based, suspension-based, and tape-based.

Figure 7
Fabrication Processes for 3D Printed Technical Ceramics



Source: BCC Research

Powder-Based Methods
Powder-based methods all have in common a powder bed from which the object emerges as a solid, formed one layer at the time. The three processes in this category differ primarily based on the technique applied to solidify the powder, which can consist of droplets of binder (binder jetting), partial sintering caused by a laser beam (selective laser sintering), or melting by infrared light (high-speed sintering).

Suspension-Based Methods
Suspension-based methods use, as printing materials, pastes or inks obtained by mixing ceramic powders with a suitable solvent and, in many cases, a binder. The object can be formed according to two methods known as direct ink writing (DIW, also known as direct ink printing) and indirect writing (IW, or indirect ink printing).

Direct ink writing consists of forming the object directly on a substrate either by paste extrusion or through the deposition of ink droplets. Indirect writing methods are based on the selective hardening of a slip, or of a slurry to which the binder is added while the object is formed. There are eleven different processes used to manufacture technical ceramics that are suspension-based.

Tape-Based Methods
Tape-based methods are based on the utilization of a ceramic tape to form the object one layer at the time. Currently, there is only one fabrication method for technical ceramics within this category.

3D Printing of Advanced Materials for Extreme Environments
Many of these techniques have been applied to the manufacture of advanced materials for extreme environments. For example, selective laser sintering has been used to produce UHTC components for gas turbines for fossil energy power production as well as functionally graded UHTCs for missile nose cones.

Robocasting has been introduced in the fabrication of hafnium diboride using a Pluronic paste. Pluronics or poloxamers are copolymers formed by two chains of polyethylene oxide with one chain of polypropylene oxide in between. These copolymers are characterized by a thermogelling behavior, which makes them particularly well-suited for 3D printing. After densification by pressureless sintering, HfB_2 components with density up to 97% of theoretical have been obtained with this process.

Laminated object manufacturing has recently been employed in the fabrication of structures with complex shape composed of the MAX phase Ti_3SiC_2. These structures were produced starting from green tapes of TiC and SiC, which were successively laminated, heat treated by pyrolysis, and infiltrated with liquid silicon.

Pressureless Sintering

Composite formulations are being developed with the purpose of manufacturing advanced materials for extreme environments by pressureless sintering. Recently, researchers at Islamic Azad University (Saveh, Iran) were able to perform pressureless sintering of ZrB_2 by adding TiC and graphite. Compacts were fired at 2000°C achieving a densification of 98% of theoretical. TiC and graphite act as grain growth inhibitors and lead to in-situ formation of TiB_2 and ZrC refractory phases.

Sol–Gel Methods

The sol–gel method is not per se a new process. In fact, it was first discovered at the end of the 19th century and extensively studied since the early 1930s. Over the years, it has been introduced for preparation of glass at low temperatures and a variety of oxide ceramics in the form of powders, fibers, aerogels, monolithic structures, and novel composites. More recently this method has been adapted also to the fabrication of non-oxide materials.

There are two traditional sol–gel routes used to produce oxide materials: polymeric and colloidal.

Polymeric Route

The polymeric or alkoxide route utilizes metal alkoxides as starting materials with the addition of proper dopants to fine-tune the properties of the final material.

There are hundreds of precursor materials commercially available with purities as high as 99.999%. A large group of common precursors are alkoxysilanes, such as tetraethoxysilane (TEOS) and tetramethoxysilane (TMOS), used in the formation of silicon dioxide or glass films. Other widely used alkoxides are aluminum, zirconium, and titanium-based compounds.

The metal alkoxides reagents, which have the generic formula M(OR)x, are mixed with an organic solvent, such as ethanol, and undergo several reactions that transform the solution into a sol (i.e., a colloidal solution) with the creation of metal-oxygen-metal bonds (M-O-M).

In fact, three reactions are generally accepted as characterizing sol–gel synthesis:

- Hydrolysis: $M(OR)_x + H_2O \rightarrow M(OR)_{x-1}(OH) + ROH$
- Condensation by alcohol elimination: $2\ M(OR)_{x-1}\ (OH) \rightarrow M_2O(OR)_{2x-3}(OH) + ROH$
- Condensation by water elimination: $2\ M(OR)_{x-1}(OH) \rightarrow M_2O(OR)_{2x-2} + H_2O$

When a sufficient number of M-O-M bonds are created, they combine forming colloidal particles, with diameters reaching up to a few hundred nanometers. This new phase constituted by nanometer solid particles suspended in a liquid is what is called sol. The initial solution preparation is often performed in a nitrogen atmosphere to prevent unwanted and uncontrolled hydrolysis in presence of air moisture.

As condensation proceeds, triggered by a heat treatment (e.g., low temperature polymerization between 100°C and 200°C) or a pH change, the colloidal particles react together forming a three-dimensional network, or gel. Gels are characterized by very high viscosity.

Acids or bases can be added during sol–gel synthesis which work as catalysts and affect the structure and morphology of the resulting gel. Also, due to the high reactivity of alkoxides with water, compounds other than alkoxides are incorporated in the starting solution, acting as stabilizers. Typical modifiers and stabilizers are alcohols, acetates, diketonates, amines, carboxilates, and organic acids.

After forming, the gel is dried to remove the water. Successive heat treatments are performed to pyrolyze the organic compounds and sinter the remaining inorganic oxides converting the gel into glass or ceramic structures. Since particles obtained by this method are very fine, sintering occurs at lower temperatures than conventional processes.

Colloidal Route

In the colloidal process, the starting materials are colloids (i.e. nanosized powders dispersed in an aqueous or organic solvent). Gel formation is promoted by adding proper initiators such as catalysts, acids, or bases. After agitation to ensure proper mixing of all its components, the sol is left to stand until gelation begins. At that point, the gel is formed in the desired shape and then is dried and sintered.

Other Routes

Several other routes have been introduced starting in the 1990s that utilize new types of precursors, including nitrates, citrates, chlorides, and organic-inorganic salts (e.g., acetates, chelates, carboxilates, carbonates, and tartrates), and organic-inorganic hybrids (e.g., organically modified ceramics and organically modified silanes) as well as combination of different precursor materials to optimize solution properties.

Sol–Gel Process for Advanced Materials for Extreme Environments

Fabrication of advanced materials for extreme environments by sol–gel methods generally consists of mixing oxide sol–gel precursors (e.g., alkoxides and chlorides) with sources of boron (e.g., boric acid) and carbon (e.g., phenolic resin and sucrose), followed by carbo- and borothermal reduction.

In the manufacture of advanced materials for extreme environments, sol–gel processing is being used primarily for producing nanocrystalline composite powders, ceramic composites, and aerogels.

The sol–gel method is becoming very attractive for producing advanced materials for extreme environments continuously reinforced ceramic matrix composites because fibers can be easily impregnated with the sol. Since the sol is comprised of nanoparticles, the composite can be sintered at lower temperatures when compared with slurry infiltration, preventing fiber degradation, matrix crystallization, and fiber/matrix interfacial reactions.

In addition, the sol–gel process can be used to form two- and three-dimensional objects as well as complex shapes, and rapid sintering techniques can be utilized such as spark plasma sintering.

Sol–gel synthesis is achieving growing interest also for fabrication of porous structures of advanced materials suitable as thermal protection materials for supersonic engines. The sol–gel process is being applied in the manufacturing of hafnium and zirconium diboride aerogels from metal oxides and boron nanoparticles.

The main current drawback of sol–gel processing, however, is excessive shrinkage during drying, which can cause cracking of the workpiece.

Hybrid Processes

Hybrid processes combine several techniques to solve specific problems existing with each method and obtain products with improved characteristics. An example is chemical vapor infiltration performed after polymer infiltration and pyrolysis to achieve compacts with higher density, while using fewer PIP cycles.

Another example is the fabrication of UHTC composites obtained by infiltrating a silicon carbide fibrous preform first with a ceramic slurry (i.e., slurry infiltration) and successively with molten silicon (melt infiltration).

Also, a carbon fiber-reinforced SiC/ZrB_2 ceramic with improved fracture toughness has been recently manufactured by nanoceramic slurry infiltration, PIP, and low-temperature hot pressing.

Latest Technological Developments, 2016 to the Present

In this section, BCC Research provides a review of technological developments regarding advanced materials for extreme environments covering the period 2016 to date.

Ceramic Composite with MAX Phase and Silicon Carbide

Rolls-Royce High Temperature Composites (Huntington Beach, CA) has created a ceramic matrix composite with improved fracture toughness consisting of silicon carbide fibers embedded in a MAX phase.

Fiber-based ceramic matrix composites such as SiCf/SiC are becoming popular thanks to their good thermal and mechanical properties as well as their low weight, which make them suitable for various industrial and aerospace applications.

In recent years, MAX phases have been receiving increasing interest for their peculiar properties between those of metals and ceramics, including their higher ductile behavior.

Rolls-Royce High Temperature Composites has introduced a MAX phase in the fabrication of continuously reinforced ceramic matrix composites to obtain a material with enhanced characteristics.

The fabrication process involves the infiltration of a porous fibrous SiC preform with a ceramic slurry comprising at least one MAX phase precursor, followed by melt infiltration with silicon.

The process starts by creating a preform with laid-up woven or unwoven silicon carbide fibers coated with an interphase material (e.g., pyrolytic carbon or boron nitride). The interphase coating acts as an interface between the silicon carbide fibers and the molten silicon during melt infiltration and also enhances toughness and crack deflection in the final composite. The porous preform is hardened by applying a silicon carbide coating by chemical vapor infiltration.

Next, the preform is vacuumed to eliminate any entrapped air and then impregnated by slurry infiltration. In addition to MAX phase precursors, the slurry contains silicon carbide particles and other additives. The MAX phase precursors are chosen so that, when the preform is successively infiltrated with molten silicon, one or more reactions occur between the molten fluid and the MAX phase precursors resulting in the formation of a MAX phase composition. The MAX phase in the final composite is preferably Ti_2AlC, Ti_2AlN, or Ti_3SiC_2, but other types can also be produced (e.g., V_2AlC, Cr_2GaC, Zr_2InC, and Nb_2AlC). The concentration of the MAX phase in the final ceramic matrix is at least 30% by weight. MAX phase precursors can be carbides, nitrides, and hydrides of transition metals, such as titanium carbide, chromium carbide, aluminum nitride, niobium nitride, zirconium hydride, and vanadium hydride.

The slurry may contain additional precursors that react with molten silicon to contribute to the formation of silicon carbide. The slurry is prepared by ball milling the solid particles with water or an organic solvent and, optionally, a polymeric binder. Slurry infiltration is typically performed at room temperature. After slurry infiltration, the preform is dried to remove the solvent.

The next step is melt infiltration with a molten liquid consisting of pure silicon or a silicon alloy (e.g., titanium-silicon). The amount of silicon is calculated on the basis that the quantity of unreacted silicon in the final workpiece must be minimized (less than 3%) to avoid degradation of its thermomechanical properties.

After infiltration and drying the ceramic component is subjected to pyrolysis and sintering. The resulting product is characterized by increased fracture toughness, high thermal shock resistance, good thermal and electrical conductivities, and improved machinability. The CMC is suitable for fabrication of turbine engine components, such as blades, vanes and combustion liners.

Other details on the fabrication process of this continuously reinforced ceramic matrix composite containing silicon carbide and MAX phase are provided in U.S. patent 9,856,176 published on Jan. 2, 2018.

UHTC Composite for Electromagnetic Shielding

Researchers at Florida State University (Tallahassee, FL) have created a ceramic matrix composite based on UHTCs and preceramic precursors. The CMC is suitable for high-temperature electromagnetic shielding applications.

Electromagnetic shielding (ES) is usually performed by a material that is capable of attenuating the transmission of an electromagnetic wave by mechanisms such as reflection, absorption, and multiple internal reflections.

The primary mechanism of ES is reflection from the shield surface due to the presence of mobile charge carriers (electrons and holes) in the shield material that interact with the electromagnetic radiation. The second most important mechanism is absorption, which usually requires the shield material to have electric and/or magnetic dipoles, which also interact with the electromagnetic radiation. The mechanism of multiple internal reflections is in general less relevant.

Conventional ES materials consist of iron powder dispersed in a polymer matrix at high concentration. This material is usually expensive. Existing alternatives to iron are carbon-based materials, such as carbon nanotubes, which, however, are not suitable for applications at very high temperatures. Therefore, there is a need for ES materials that can be used at temperatures greater than 700°C and under harsh conditions.

Polymer-derived ceramics (PDCs) are an emerging group of materials with good high-temperature thermomechanical properties. They exhibit thermal stability up to 2000°C and better oxidation resistance than SiC or Si_3N_4. In addition, PDCs can be formed into components with complex shapes.

Researchers at Florida State University have combined PDCs with UHTCs to prepare a composite material with desirable electromagnetic shielding properties under extreme environments (i.e., at very high temperatures and strong oxidative conditions).

The CMC is made from UHTC particles and a liquid ceramic precursor with weight ratio of approximately 1:1. Although any known UHTC can be used, the preferred material is zirconium diboride. The PDC precursor, instead, is an organosilicon polymer, such as polysiloxane, polycarbosiloxane, or polyborosilane. Typically, a PDC precursor that converts to SiC during sintering is employed in this process, although other possible options are polymer precursors that form BN, Si_3N_4, and AlN.

The UHTC particles are stirred in the liquid preceramic precursor and sonicated. The mixture is then heated to cure the liquid preceramic precursor by crosslinking. Next, the material is ball milled to obtain smaller solid particles. These particles exhibit a core-shell structure, in which the core consists of the UHTC and the shell is formed by the cured preceramic precursor.

The particles are compacted to the desired shape by either cold or hot pressing. For example, aircraft nosecones or portions of submarines can be made with this process.

Finally, the workpiece is sintered. During this step the preceramic precursor is converted to a ceramic creating a ceramic matrix composite.

The UHTC-PDC CMC developed at Florida State University is described in U.S. patent application 2019/0256426, published on Oct. 22, 2019.

MAX Phase for Gas Turbines

Ansaldo Energia (London, U.K.) has recently produced gas turbine components containing a MAX phase.

The current generation of gas turbines is designed to withstand very high temperature gases. Standard materials for hot gas turbine parts are nickel superalloys. These superalloys are characterized by a density of approximately 8 g/cm^3, which causes high centrifugal forces that generate undesired stresses on components such as blades, especially in big turbines.

MAX phases are a relatively new type of ternary ceramics with density of approximately 4 g/cm^2. Therefore, they are very promising materials for production of very large gas turbines.

The MAX phase developed by Ansaldo Energia is either a single phase Ti_2AlC or a two-phase Ti_2AlC-Ti_3AlC_2 ceramic having Ti_2AlC between 60% and 95% of the total. Alternately, the material can be made from Ti_3SiC_2 or Ti_3SiC_2-Ti_4SiC_3 with 60-95% Ti_3SiC_2. Another possibility is a composite comprising both Ti_2AlC and Ti_3SiC_2, with 40–90% Ti_3SiC_2.

The MAX phase is used to fill cavities of the gas turbine structure and is either mixed or coated with a nickel or cobalt-based superalloy. Coating is performed using a spraying method such as cold plasma spray. The MAX phase ceramic is then subjected to sintering by hot isostatic pressing.

Before being filled with the MAX phase, the metal hollow structure can be pre-oxidized to form a thin thermally grown oxide that prevents interdiffusion with the MAX phase.

In addition to have lower density, the MAX phase exhibits good thermomechanical properties, including a thermal expansion coefficient greater than $8x10^{-6}$ K^{-1}, fracture toughness greater than 5 MPa $\cdot$ $m^{1/2}$, and high oxidation resistance.

The gas turbine component with a MAX phase introduced by Ansaldo Energia and its fabrication method are detailed in U.S. patent 10,612,382, awarded on April 7, 2020.

Low-Temperature Synthesis of Zirconium Diboride Powder

Scientists at North China Electric Power University (Beijing, China) have introduced a new method for producing zirconium diboride powder by low-temperature synthesis.

There are various technologies for preparing zirconium diboride powder, the most important of which are direct synthesis, carbothermal/borothermal reduction, electrolytic salt bath, self-propagating high-temperature synthesis (SHS), and sol–gel.

Direct synthesis consists in the high-temperature reaction between metallic zirconium and non-metallic boron under inert atmosphere or vacuum. High purity ZrB_2 powder is obtained, but this method utilizes expensive reagents and requires high temperatures and long reaction times.

The carbothermal/borothermal method uses zirconium dioxide, boron, and carbon black as raw material. It is currently the most common process for industrial quantities. Although raw materials are easily available at relatively low cost, this method is characterized by low reaction efficiency, requires temperatures as high as 1750°C and a long reaction time. In addition, particles with small particle size are difficult to produce.

The electrolytic salt bath method consists in the electrolysis of a molten salt containing a zirconium compound and boron oxide. This process generates powders with medium purity, often agglomerated, and is energetically inefficient.

SHS is based on zirconium powder, boric anhydride and magnesium powder. The process creates a low-purity product with irregular particle shape and broad particle size distribution, often agglomerated.

The sol–gel method utilizes zirconium n-propoxide, glucose and boric acid as starting materials. These materials are generally expensive, and the process is quite complex and characterized by low output.

To overcome some of these drawbacks, the Chinese researchers developed a low-temperature molten salt method that delivers a pure, well-crystallized zirconium boride powder synthesized in air and at very low temperature, while using raw materials that are readily available. In addition, the molten salt can be recycled, contributing to reduce production costs. This method is suitable for mass production.

The process starts by mixing a zirconium compound such as zirconium hydroxide with a boron compound, usually boric acid. The mixture is combined with a molten chloride salt (e.g., sodium chloride and potassium chloride) to obtain a zirconium diboride precursor. This precursor is heated up to 1100°C for a maximum of 6 hours, cooled to room temperature, and washed with hot distilled water several times, obtaining black zirconium diboride powder.

Further details regarding this process are provided in Chinese patent CN109231232, issued on Jan. 18, 2019.

Other Relevant R&D Activities

The table below briefly summarizes other relevant R&D activities currently in progress at various research institutions around the world.

Table 16
Other Relevant R&D activities, 2020

Research Organization	Location	R&D Activities
Air Force Research Laboratory	Wright-Patterson Air Force Base, OH	Preparation of UHTC coatings for metallic tungsten substrates by selective laser melting
Chinese Academy of Sciences	Shanghai, China	Investigation of high-temperature ablation behavior of pressureless sintered $Ta_{0.8}Hf_{0.2}C$-based UHTCs
		Evaluation of bubble phenomenon during fabrication of ultrahigh temperature ceramics
Chinese Academy of Sciences	Shenyang, China	Fabrication of ZrB_2-SiC coatings with $TaSi_2$ addition for enhanced oxidation resistance
Chongqing University of Science and Technology	Chongqing, China	Development of a temperature dependent fracture toughness model for particle-reinforced UHTCs
CNR-ISTEC	Faenza, Italy	Investigation of UHTCs for thermodynamic solar energy generation at high temperature
		Analysis of the ablation behavior of UHTC composites and role of metal silicide addition
CNRS/Université de Poitiers/ENSMA	Poitiers, France	Evaluation of microstructure-oxidation resistance relationship in Ti_3AlC_2 MAX phase
Delft University of Technology	Delft, the Netherlands	Evaluation of ultrahigh temperature ablation behavior of MoAlB ceramics under an oxyacetylene flame
Donghua University	Shanghai, China	Fabrication of sol–gel derived porous UHTCs for lightweight components

Research Organization	Location	R&D Activities
Duy Tan University	Da Nang, Vietnam	Simulation of spark plasma sintered TiB_2 UHTCs
Forschungszentrum Jülich GmbH	Jülich, Germany	Production of Cr_2AlC MAX phase for thermal barrier coatings
Guangdong University of Technology	Guangzhou, China	Fabrication of highly dense high-entropy boride ceramics with ultrahigh hardness
Harbin Institute of Technology	Harbin, China	Prediction of UHTC melting temperature by machine learning
		Evaluation of the catalytic behavior of ZrB_2-SiC-W UHTC at moderate temperatures
Imperial College London	London, U.K.	Production of hafnium diboride by additive manufacturing
Indian Institute of Science	Bangalore, India	Investigation of the thermochemical stability of ZrB_2-SiC UHTCs under hypersonic aerothermodynamic conditions
Iowa State University	Ames, IA	Investigation of oxidation behavior of SiC/ZrB_2 UHTCs at 2000°C and low pressure (100 Torr)
Korea Institute of Ceramic Engineering and Technology	Icheon, South Korea	Utilization of UHTC oxidation-resistant and anti-ablation coatings for carbon-carbon composites
Missouri University of Science and Technology	Rolla, MO	Fabrication of dense high-entropy boride ceramics by two-step spark plasma sintering
		Prediction of fracture toughness of ZrB_2-based UHTCs by phase-field modeling
		Synthesis of single-phase high-entropy carbide powders
National University of Kyiv	Kiev, Ukraine	Reactive sintering of TiB_2-SiC-CNT ceramics
National University of Science and Technology MISIS	Moscow, Russia	Fabrication of ultrahigh temperature nonstoichiometric hafnium carbonitride by combustion synthesis and spark plasma sintering
		Combustion synthesis of UHTCs based on $(Hf,Ta)B_2$
North Carolina State University	Raleigh, NC	Development of polymer-derived UHTC composite as microwave-absorbing material for harsh environment applications
North University of China	Taiyuan, China	Joining of SiC/ZrB_2 UHTCs with nickel fillers
Russian Academy of Sciences	Moscow, Russia	Investigation of the effect of air humidity on the oxidation stability of HfB_2-SiC UHTCs
Shahid Beheshti University	Tehran, Iran	Investigation of mechanical, structural, and thermodynamic properties of TaC-ZrC UHTCs using first principle methods
Southwest Jiaotong University	Chengdu, China	Development of SiC/ZrB_2 UHTCs with higher oxidation resistance
Technische Universität Darmstadt	Darmstadt, Germany	Evaluation of UHT CMCs produced from polymer-derived ceramics
The University of Arizona	Tucson, AZ	Development of an ablation model for UHTCs
The University of Sheffield	Sheffield, U.K.	Fabrication of Ti_3SiC_2-$TiSi_2$-TiC MAX phase composite by reactive spark plasma sintering

Research Organization	Location	R&D Activities
Universita` degli Studi di Cagliari	Cagliari, Italy	Fabrication of ultrahigh temperature porous graded ceramic for solar energy applications
University of Birmingham	Birmingham, U.K.	Development of a slurry injection technique for continuously reinforced UHTC composites
University of Naples	Naples, Italy	Characterization of UHTC composites by arc-jet wind tunnel
University of Rajshahi	Rajshahi, Bangladesh	Characterization of thermomechanical properties of recently synthesized Lu_2SnC MAX phase for thermal barrier coatings
University of Tennessee	Knoxville, TN	Fabrication of niobium carbide UHTCs for fully microencapsulated fuels
Vikram Sarabhai Space Centre	Thiruvananthapuram, India	Synthesis of zirconium diboride based UHTC via preceramic route
Wuhan University of Technology	Wuhan, China	Fabrication of fine-grained UHTCs by spark plasma sintering at 250 MPa and 1850°C
Xi'an Jiaotong University	Xi'an, China	Evaluation of oxidation behavior of ZrB_2-based UHTCs under compressive stress

Source: BCC Research

Chapter 5

Global Markets

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Chapter 5: Global Markets

Outline of the Analysis

In this chapter, BCC Research provides an in-depth analysis of the market for advanced ceramic materials for extreme environments.

To evaluate the global market for these products, BCC Research has grouped revenues according to four key segments:

- Aerospace and defense.
- Energy.
- Mechanical/chemical/metallurgical.
- Others.

The principal objective of this chapter is to examine the market for advanced ceramic materials for extreme environments within the four key segments, focusing on the following topics:

Current market status.

- Trends for growth.
- Market forecast.

The result of this analysis is an assessment of the current market for advanced materials for extreme environments (for the period 2018 through 2020) with growth projections for the period 2020 through 2025 within each market segment.

The global market analysis conducted by BCC Research is based on segmenting the world market into four major regions: U.S., Europe, Asia-Pacific, and Rest of the World. Europe includes all 27 countries belonging to the European Union, plus Switzerland, United Kingdom, and Norway. Asia-Pacific includes Brunei, Cambodia, China, Indonesia, Japan, Laos, Macau, Malaysia, Philippines, Singapore, Thailand, Taiwan, Hong Kong, North Korea, South Korea, and Vietnam. All the remaining countries are grouped under the Rest of the World segment.

Global Market Summary

The global market for advanced ceramic materials for extreme environments was valued at $2.9 billion in 2018, increased to $3.0 billion in 2019, and is estimated to be valued at $2.9 billion in 2020, corresponding to a CAGR of 5.7% over the two-year period. The coronavirus pandemic is the culprit for the expected sales drop from 2019 to 2020.

Advanced materials for extreme environments are available in various compositions, microstructures, and configurations and find their main application in sectors such as aerospace and defense, energy, and mechanical/chemical/metallurgical.

In 2020, 92.7% of total revenues, corresponding to $2.7 billion are estimated to be generated by the mechanical/chemical/metallurgical sector. The most popular applications of advanced materials for extreme environments within this segment are for fabrication of wear and corrosion resistant devices, such as cutting tools, and high-temperature parts, such as crucibles.

Advanced materials for extreme environments for aerospace and defense also represent a relevant share of the market, with estimated total revenues of $153 million in 2020, equal to 5.3% of the total. Within this segment, advanced ceramic materials for extreme environments find use primarily in the manufacturing of components for aircraft and propulsion systems.

The remaining applications are estimated to account for a combined 2.0% of the global market in 2020.

There are various drivers, restraints, challenges, and opportunities that will impact market growth of advanced ceramic materials for extreme environments during the next five years. They are summarized in the table below.

Table 17
Drivers, Restraints, Challenges, and Opportunities in the Market for Advanced Ceramic Materials for Extreme Environments

Market Dynamics	
Drivers	Improved manufacturing processes have recently been introduced.
	Advanced sintering methods, such as spark plasma sintering, have become available.
	Low cost processes, such as additive manufacturing, have also been introduced lately.
	Production of components with various formulations (borides, nitrides, carbides), different microstructure (monoliths and composites), configurations (bulk and coatings) and properties (UHTCs, MAX phase ceramics, and high-entropy ceramics) is possible, allowing to meet the requirements needed in various applications.
	Numerous research activities are in progress resulting in the creation of materials with better properties.
	Traditional applications in the mechanical/chemical/metallurgical and aerospace/defense sectors are expected to resume growth although at a moderate pace once the coronavirus pandemic is over.
	Further penetration of these materials in the fabrication of wear and corrosion resistant components, such as cutting tools, is occurring.

Market Dynamics	
	Artificial intelligence is contributing to properties enhancement. Machine learning is being used to predict actual melting temperatures and other properties of advanced materials for extreme environments facilitating the development of new materials. Machine-learning force fields are allowed for the simulation of advanced materials for extreme environments in harsh environments.
Restraints	Some fabrication processes are too labor-intensive for high volume manufacturing.
	Most fabrication processes are energy-intensive, since they require high temperature and high pressure.
	High-purity materials are the most difficult to manufacture.
Challenges	There are limited testing techniques able to reproduce the effective operating conditions of these materials. For example, arc-jet testing is considered a very promising ground-based method for simulating reentry conditions and evaluate the mechanical, chemical and thermal behavior of advanced materials for extreme environments under re-entry conditions, but the reliability of this testing method is not well-known.
	Joining methods for advanced materials for extreme environments require further development.
Opportunities	3D printing is allowing for the creation of components with tailored properties and complex geometries, including flexible devices.
	Emerging applications are occurring in energy and electronics.
	The coating segment offers unexplored growth opportunities.
	Lightweight components can now be produced due to the introduction of new fabrication processes.

Source: BCC Research

As a result, BCC Research projects that sales of these products will increase at a moderate CAGR of 5.7% from 2020 to 2025, reaching $3.8 billion by 2025.

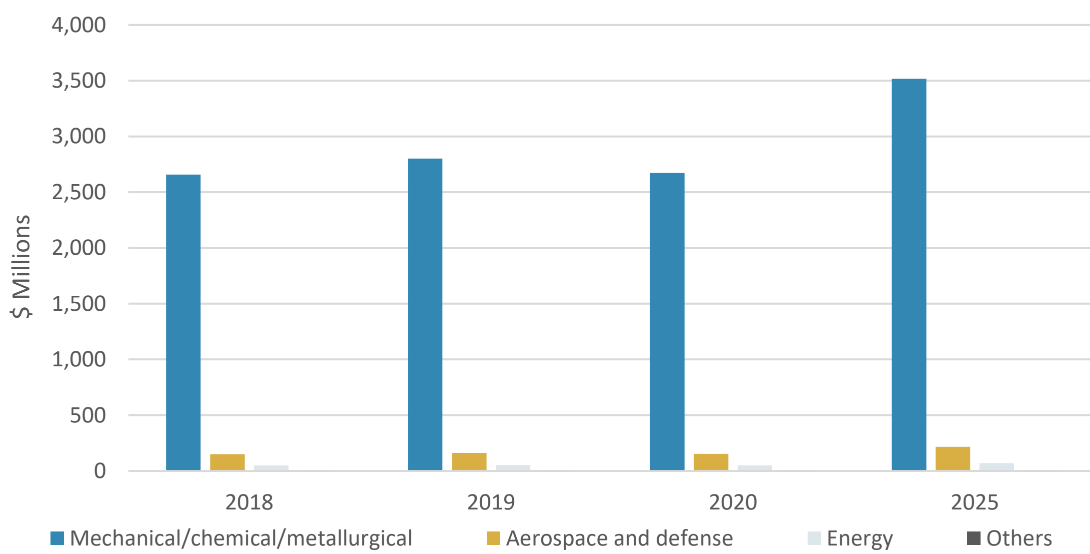
Sales data are summarized in the next table and a graphic representation is provided in the following figure.

Table 18
Global Market for Advanced Ceramic Materials for Extreme Environments, by Application Industry, Through 2025
($ Millions)

Application Industry	2018	2019	2020	2025	CAGR% 2020-2025
Mechanical/chemical/metallurgical	2,658	2,802	2,674	3,518	5.6
Aerospace and defense	151	161	153	217	7.2
Energy	50	53	51	70	6.5
Others	6	6	6	8	5.9
Total	2,865	3,022	2,884	3,813	5.7

Source: BCC Research

Figure 8
Global Market for Advanced Ceramic Materials for Extreme Environments, by Application Industry, 2018-2025
($ Millions)



Source: BCC Research

Current Market Status

The following sections review the current status of the global market for advanced materials for extreme environments. Analysis is based on material group, composition, microstructure, configuration, application, and region.

Market by Material Group

The three material groups covered in this section are ultrahigh temperature ceramics (UHTCs), MAX phase products (MAX phase), and high-entropy ceramics (HECs). As discussed in the technology section, each of these groups of materials is characterized by specific properties and functionalities, which also determine their fields of applications.

As summarized in the table below and in the following figure, based on the analysis by BCC Research, sales of UHTCs currently represent by far the largest segment of the market for advanced materials for extreme environments. Due primarily to the global slowdown related to the COVID-19 pandemic, sales of products based on these materials are estimated to increase at a CAGR of 0.3% through 2020, going from $2.9 billion in 2018 to $3.0 billion in 2019, and are projected to reach slightly over $2.9 billion by the end of 2020, corresponding to a share of 98.8% of the total in 2020.

MAX phase ceramics have been expanding at a CAGR of 1.4% during the two-year period, from $35 million in 2018 to $36 million by the end of 2020. This segment is estimated to account for 1.2% of the total market in 2020.

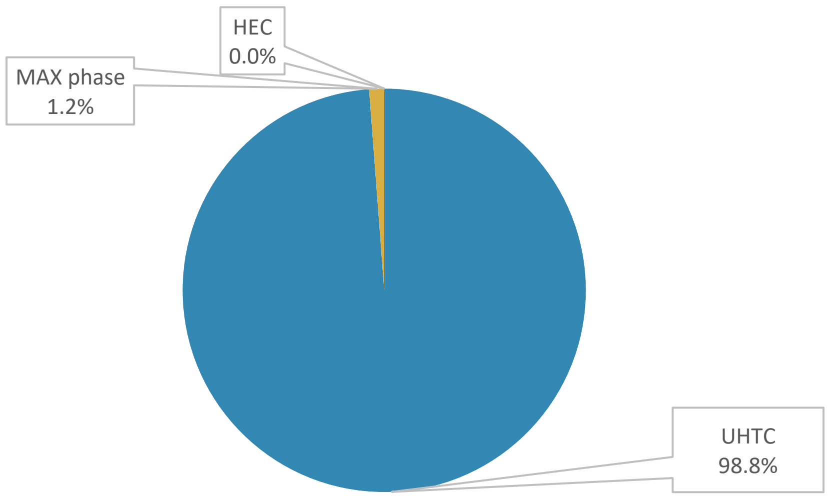
HECs are still for the most part in the development stage and their current market is negligible. As a result, the total market for advances material products is projected to reach $2.9 billion in 2020, rising at a CAGR of 0.3% during the considered period.

Table 19
Global Market for Advanced Ceramic Materials for Extreme Environments, by Material Group, Through 2020
($ Millions)

Material Group	2018	2019	2020	CAGR% 2018-2020
UHTC	2,830	2,985	2,848	0.3
MAX phase	35	37	36	1.4
HEC	–	–	–	–
Total	2,865	3,022	2,884	0.3

Source: BCC Research

Figure 9
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Material Group, 2020
(%)



Source: BCC Research

Market by Composition

The next table summarizes the market breakdown for the 2018-2020 period, by composition. The term composition refers to the material forming the primary phase, which corresponds to the matrix material in case of composites. As previously discussed, advanced ceramic materials for extreme environments consist mainly of borides, carbides, or nitrides.

At the present time, nitrides represent the largest segment of the market. Nitrides consist chiefly of ceramics based on boron nitrides, which find their main use in the mechanical/chemical/metallurgical sector for super-hard cutting tools, sputtering targets for hard coatings, and high temperature-resistant crucibles and evaporation boats. This segment is estimated to be worth $2.5 billion in 2020, growing at a CAGR of 0.3% during the two-year period, and corresponding to an 85.6% share of the total by the end of 2020.

Borides account for the second-largest share of the market for advanced materials for extreme environments at 7.6% of the total in 2020. Currently, borides find application primarily in components and coatings for the aerospace industry and in sputtering targets. The market for these products is estimated to reach $218 million in 2020, expanding at a CAGR of 0.9% since 2018.

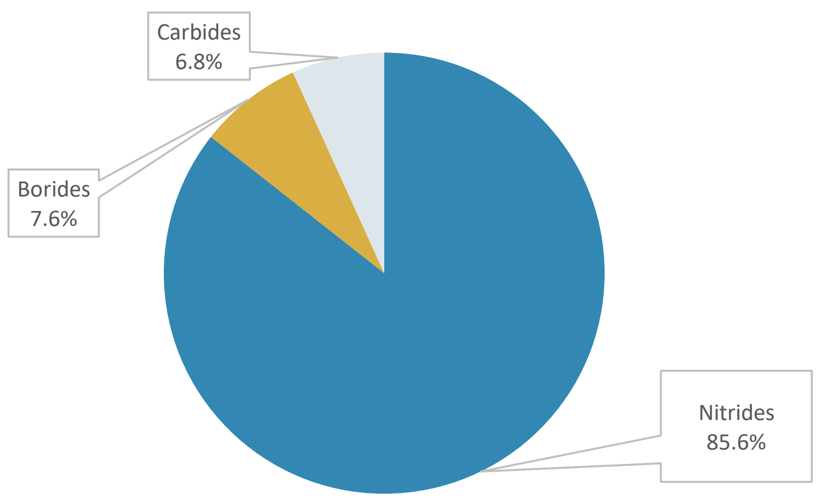
Carbides also represent a significant share at 6.8% of the total in 2020. Carbides have broad applications, since they are employed to fabricate a variety of components and coatings within the aerospace, energy, and mechanical/chemical/metallurgical sectors. Their market is estimated to reach $196 million in 2020, rising at a CAGR of 0.5% since 2018.

Table 20
Global Market for Advanced Ceramic Materials for Extreme Environments, by Composition, Through 2020
($ Millions)

Composition	2018	2019	2020	CAGR% 2018-2020
Nitrides	2,457	2,593	2,470	0.3
Borides	214	226	218	0.9
Carbides	194	203	196	0.5
Total	2,865	3,022	2,884	0.3

Source: BCC Research

Figure 10
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Composition, 2020
(%)



Source: BCC Research

Market by Microstructure

The next tables and figures supply the current market breakdown by microstructure. Microstructure refers to monolithic or composite ceramics.

Composite advanced materials for extreme environments represent the largest group of products. With estimated global sales of $2.1 billion in 2020, this segment accounts for 73.6% of the total. Revenues are expanding at a CAGR of 0.3% during the two-year period. Composite advanced ceramic materials for extreme environments are used in the fabrication of both solid ceramics (or bulk ceramics) and coatings within a wide range of applications. Composites are more common than monoliths due to various issues still existing with the manufacturing process of monoliths.

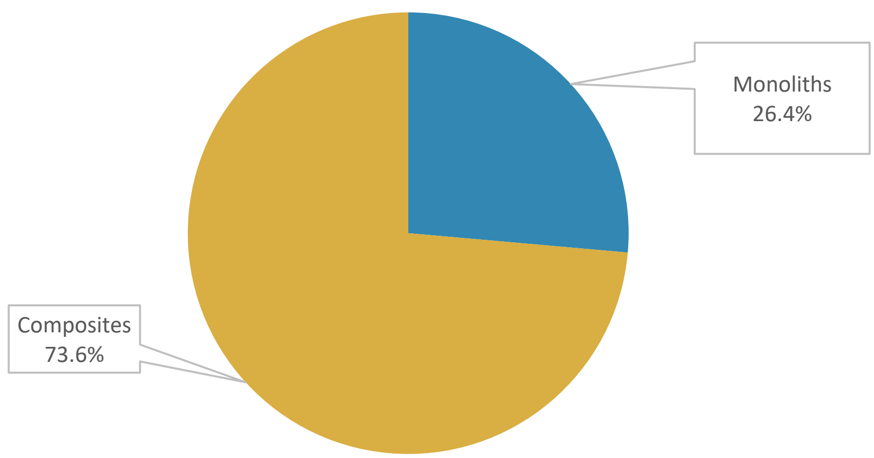
Sales of monolithic products, which are estimated at $760 million in 2020 (or 26.4% of total sales), have been expanding at a CAGR of 0.3% since 2018, primarily driven by the fabrication of sputtering targets and other high-purity components and coatings for very demanding applications.

Table 21
Global Market for Advanced Ceramic Materials for Extreme Environments, by Microstructure, Through 2020
($ Millions)

Microstructure	2018	2019	2020	CAGR% 2018-2020
Composites	2,110	2,229	2,124	0.3
Monoliths	755	793	760	0.3
Total	2,865	3,022	2,884	0.3

Source: BCC Research

Figure 11
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Microstructure, 2020
(%)



Source: BCC Research

Market by Configuration

The next tables and figures supply the current market breakdown by configuration. Two main configurations have been identified:

- Bulk, which include components of many different shapes, such as crucibles, bearings, cutting tools and inserts, turbine blade parts, freestanding thick-walled structures, tubes, rods, plates, blocks, and rings.

- Coatings, such as thermal and environmental protection barriers (TPBs and EPBs) applied by various deposition technologies.

Bulk advanced ceramic materials for extreme environments represent the largest group of products. With estimated global sales of $2.7 billion in 2020, this segment accounts for 95.0% of the total. Revenues are expanding at a CAGR of 0.3% during the two-year period. Bulk ceramics are popular in a variety of applications across multiple sectors.

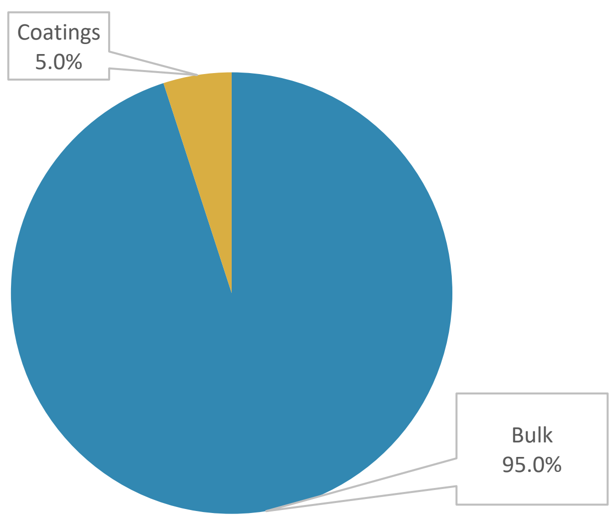
Coatings are estimated to be valued at $143 million in 2020, or 5.0% of the total. Coatings are mainly used in as TPBs and EPBs in the aerospace industry and as coatings for cutting tools and other wear resistant components.

Table 22
Global Market for Advanced Ceramic Materials for Extreme Environments, by Configuration, Through 2020
($ Millions)

Configuration	2018	2019	2020	CAGR% 2018-2020
Bulk	2,724	2,878	2,741	0.3
Coatings	141	144	143	2.4
Total	2,865	3,022	2,884	0.3

Source: BCC Research

Figure 12
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Configuration, 2020
(%)



Source: BCC Research

Market by Application Industry

The table and figure below provide the current market breakdown for advanced ceramic materials for extreme environments by application.

At the present time, the mechanical/chemical/metallurgical sector represents the largest field of application for advanced materials for extreme environments. This segment is estimated to generate revenues of $2.7 billion by the end of 2020, corresponding to 92.7% of the total market. Advanced materials for extreme environments are primarily used for fabrication of cutting tools and other wear resistant components, parts for high temperature furnaces and metal melting, and sputtering targets. Revenues generated by these products are growing at a CAGR of 0.3% through 2020.

The second-largest share of sales is attributed to the aerospace and defense industry, with estimated revenues of $153 million in 2020 (or 5.3% of total sales), corresponding to a CAGR of 0.7% during the two-year period. Within this industry, the main application is in the fabrication of aircraft components, re-entry vehicles, rockets, and armors.

Energy is the next largest sector. Growing at a CAGR of 1.0% since 2018, sales of advanced materials for extreme environments within this sector are projected to reach $51 million in 2020, corresponding to a share of 1.8% of the total. Currently, the main application for these ceramics is in the fabrication of industrial gas turbines and parts for nuclear reactors.

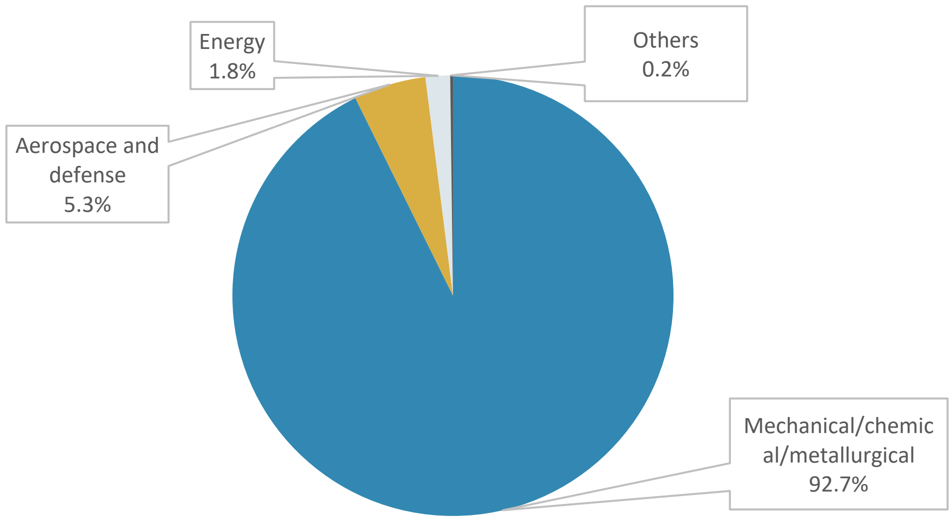
Other applications form a very small segment at the present time with stable revenues estimated at $6 million, or 0.2% of the total market.

Table 23
Global Market for Advanced Ceramic Materials for Extreme Environments, by Application Industry, Through 2020
($ Millions)

Application Industry	2018	2019	2020	CAGR% 2018-2020
Mechanical/chemical/metallurgical	2,658	2,802	2,674	0.3
Aerospace and defense	151	161	153	0.7
Energy	50	53	51	1.0
Others	6	6	6	–
Total	2,865	3,022	2,884	0.3

Source: BCC Research

Figure 13
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Application Industry, 2020
(%)



Source: BCC Research

Market by Region

The table below shows the regional revenue breakdown for the period 2018 through 2020. The next figure displays the repartition of 2020 sales among the different regions.

The U.S. is the largest consumer of advanced ceramic materials for extreme environments. In this region, revenues for these products have been increasing at a CAGR of 0.5% since 2018. Revenues rose from $1.1 billion in 2018 (38.2% of the total) to $1.2 billion in 2019 (38.3%). Sales are estimated to reach $1.1 billion in 2020, corresponding to a share of 38.3% of the total.

The Asia-Pacific region represents the second-largest market for advanced materials for extreme environments. In this region, sales have been increasing at a CAGR of 0.3% since 2018. Revenues grew from $929 million in 2018 (32.4% of the total) to $979 million in 2019 (a 32.4% share). Sales are projected to reach $934 million in 2020, corresponding also to 32.4% of the total

In Europe, sales of advanced materials for extreme environments are projected to increase at a CAGR of 0.3% during the two-year period. Revenues rose from $598 million in 2018 (20.9% of the total) to $629 million in 2019 (20.8%) and are expected to amount to $601 million at the end of 2020 (20.8%).

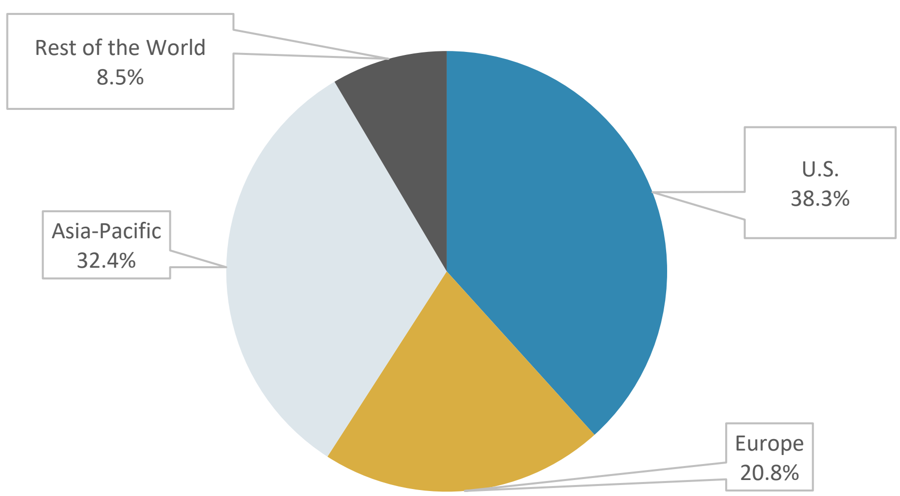
In the Rest of the World, sales of these products increased from $243 million in 2018 (8.5%) to $257 million in 2019 (8.5%), and are estimated to be valued at $244 million in 2020 (a stable 8.5% of the total market), corresponding to a 0.4% CAGR during the two-year period.

Table 24
Global Market for Advanced Ceramic Materials for Extreme Environments, by Region, Through 2020
($ Millions)

Region	2018	2019	2020	CAGR% 2018-2020
U.S.	1,095	1,157	1,105	0.5
Asia-Pacific	929	979	934	0.3
Europe	598	629	601	0.3
Rest of the World	243	257	244	0.4
Total	2,865	3,022	2,884	0.3

Source: BCC Research

Figure 14
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Region, 2020
(%)



Source: BCC Research

Market Growth Trends

To develop growth forecasts for advanced ceramic materials for extreme environments through 2025, various factors that will influence this market are analyzed in the next sections, including industry growth, technological trends, and regional trends.

Mechanical/Chemical/Metallurgical

There are three main segments within this sector that are relevant to future growth of the market for advanced materials for extreme environments: wear and corrosion resistant components, high-temperature resistant parts, and sputtering targets.

Wear and Corrosion Resistant Components

More specifically, wear and corrosion-resistant parts include cutting tools and tool inserts, bearings, valves, nozzles, crushers, pump components, and mill balls.

As shown in the next table, the market for wear and corrosion resistant parts will be characterized by overall good growth during the 2020-2025 period. This market is estimated to be worth $270.0 billion in 2025, rising at a 6.6% CAGR since 2020.

Bearings not only account for the largest share, but they also represent the fastest growing segment. Rising at a CAGR of 8.4% during the next five years, bearings are forecast to reach $118.6 billion by the end of 2025, corresponding to a share of 43.9%, as displayed in the following figure.

Sales of valves will be characterized by more moderate growth. Increasing at a CAGR of 4.6% through 2025, revenues for these products are estimated to reach $99.7 million in 2025, or 36.9% of the total.

Cutting tools and inserts are projected to rise at a 7.4% CAGR, generating global revenues of $39.6 billion by the end of 2025, or 14.7% of the total.

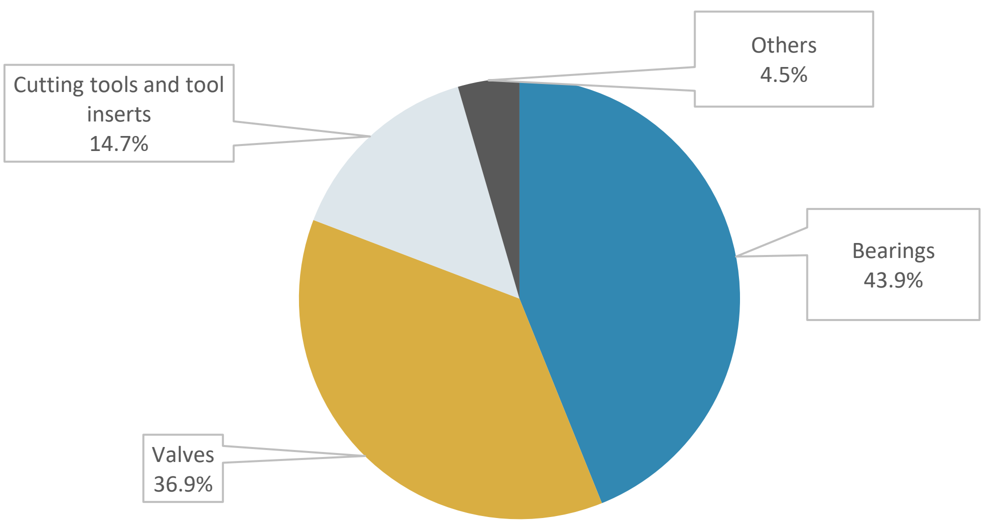
All the remaining components will be valued at $12.1 billion in 2025 (or 4.5%), corresponding to a CAGR of 3.7% during the forecast period.

Table 25
Global Market for Wear and Corrosion Resistant Components, by Type, Through 2025
($ Billions)

Type	2019	2020	2025	CAGR% 2020-2025
Bearings	83.6	79.1	118.6	8.4
Valves	83.8	79.6	99.7	4.6
Cutting tools and tool inserts	29.3	27.7	39.6	7.4
Others	10.6	10.1	12.1	3.7
Total	207.3	196.5	270.0	6.6

Source: BCC Research

Figure 15
Estimated Global Market Shares of Wear and Corrosion Resistant Components, by Type, 2025
(%)



Source: BCC Research

High-Temperature Resistant Parts
High-temperature resistant parts belong to the category of ceramic refractories. There are three types of ceramic refractories: bricks and stackable shapes, unshaped refractories, and other parts.

Bricks and stackable shapes are primarily used to build furnaces and include bricks, blocks, tiles and similar products. Unshaped products (also known in the refractory industry as monoliths) are furnace elements formed on site and consist primarily of liners and components for furnace repairs. These two types of refractory products are mostly made from sintered clay.

Other parts consist of crucibles, ladles, kiln furniture, boards, nozzles, protection tubes and other components typically used to handle the materials being processed at high temperature.

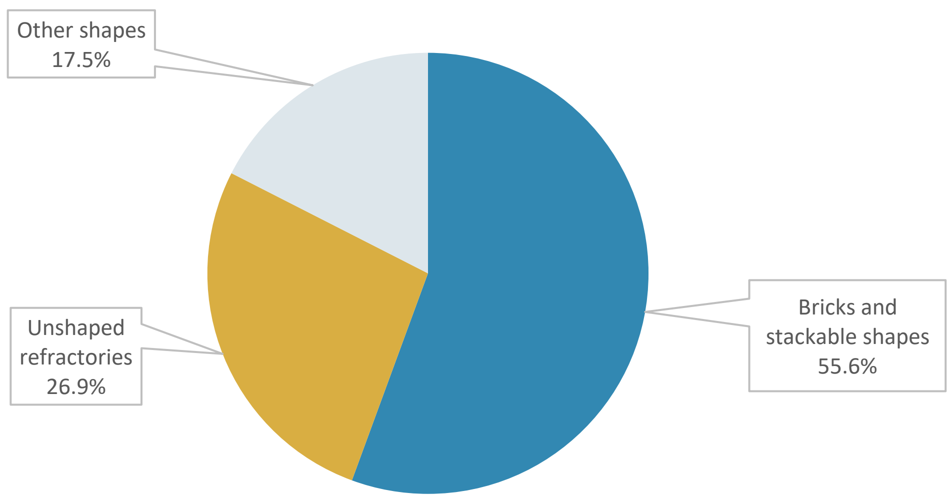
As shown in the next table, the general refractory market will generate global revenues of $43.5 billion in 2025 and will by characterized by slow growth, with a CAGR of 4.3%. Sales of crucibles and other shapes are also estimated to expand moderately with a CAGR of 4.2% during the forecast period, generating revenues of $7.6 billion by the end of five-year period.

Table 26
Global Market for Ceramic Refractories, by Type, Through 2025
($ Billions)

Type	2019	2020	2025	CAGR% 2020-2025
Bricks and stackable shapes	21.3	20.1	24.2	3.8
Unshaped refractories	9.6	9.0	11.7	5.4
Other parts	6.5	6.2	7.6	4.2
Total	37.4	35.3	43.5	4.3

Source: BCC Research

Figure 16
Estimated Global Market for Ceramic Refractories, by Type, 2025
(%)



Source: BCC Research

Sputtering Targets
Sputtering is one of the most popular coating processes used by the advanced materials industry to deposit thin films (i.e., films with a thickness below 5 microns). Sputtering targets are high-value products that provide the material for creating the film during the sputtering process.

As shown in the next table and figure, the global market for sputtering targets is estimated to be valued at $4.1 billion in 2025, up at a CAGR of 5.2% from 2020. Oxides are estimated to account for the largest share of the market in 2020, with revenues of $1.6 billion (or 39.4% of the total), followed by metals and pure elements, which are estimated to be valued at $1.4 billion (a 34.4% share).

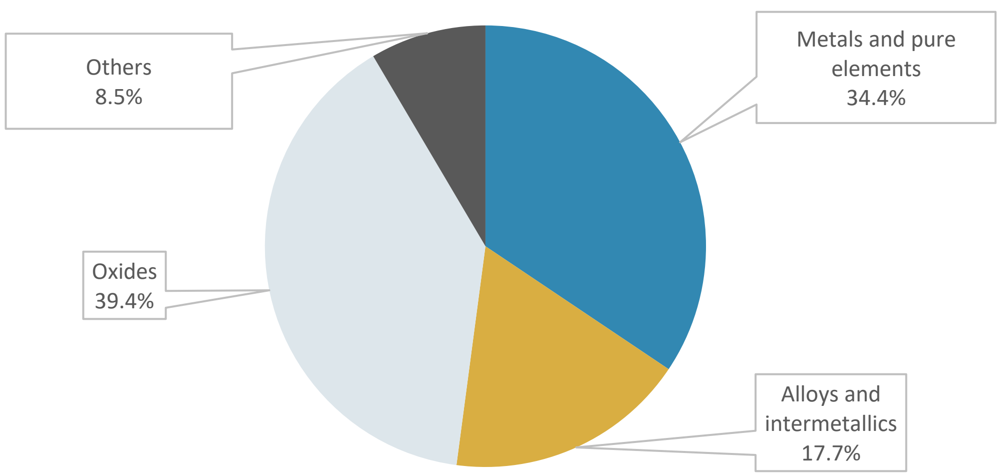
Alloy targets are estimated to produce revenue of $736 million in 2020, or 17.7% of the total, while other materials, which also include advanced materials for extreme environments, are projected to be valued at $352 million, corresponding to an 8.5% share.

Table 27
Global Market for Sputtering Targets, by Type of Material, Through 2025
($ Millions)

Type of Material	2019	2020	2025	CAGR% 2020-2025
Oxides	1,210	1,142	1,632	7.4
Metals and pure elements	1,207	1,143	1,424	4.5
Alloys and intermetallics	698	660	736	2.2
Others	287	272	352	5.3
Total	3,402	3,217	4,144	5.2

Source: BCC Research

Figure 17
Estimated Global Market Shares of Sputtering Targets, by Type of Material, 2025
(%)



Source: BCC Research

The following table and figure, instead, provide the breakdown of target revenues by region for the same period.

The Asia-Pacific region represents the largest consumer of sputtering targets. Sales of sputtering targets in this region are projected to grow at a 5.3% CAGR during the next five years, from $2.0 billion in 2020 to $2.6 billion in 2025 (a 63.2% market share).

The U.S. accounts for the second-largest share of the market. Sales of sputtering targets will reach $747 million in 2025 (or 18.0% of the total), growing at a CAGR of 5.3% during the forecast period.

In Europe, revenues are projected to increase at a 5.0% CAGR during the five-year period, and generate revenues of $684 million in 2025, or 16.5% of the total market.

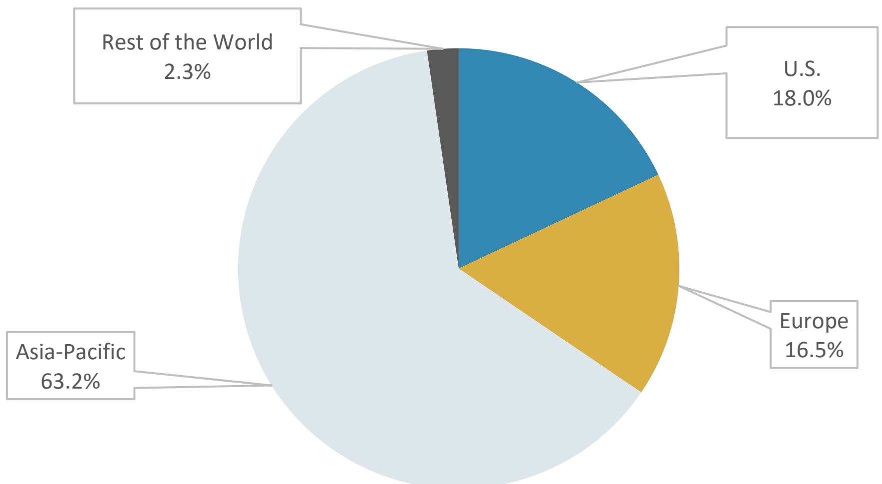
In the Rest of the World, sputtering target sales are forecast to increase moderately at a CAGR of 4.6% through 2025. Revenues in this region are estimated to reach $94 million in 2025, corresponding to a 2.3% share of the total market.

Table 28
Global Market for Sputtering Targets, by Region, Through 2025
($ Millions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	611	578	747	5.3
Asia-Pacific	2,143	2,027	2,619	5.3
Europe	569	537	684	5.0
Rest of the World	79	75	94	4.6
Total	3,402	3,217	4,144	5.2

Source: BCC Research

Figure 18
Estimated Global Market Shares of Sputtering Targets, by Region, 2025
(%)



Source: BCC Research

Aerospace and Defense

The future market for advanced materials for extreme environments will be affected by general growth of the aerospace and defense industries, as well as by the demand for specific products such as thermal barrier coatings and armors.

Aerospace

The aerospace industry (including aircraft, aircraft parts, space vehicles, engine parts, maintenance and repair, and training and simulation) is forecast to be characterized by moderate growth, overall, from 2020 through 2025.

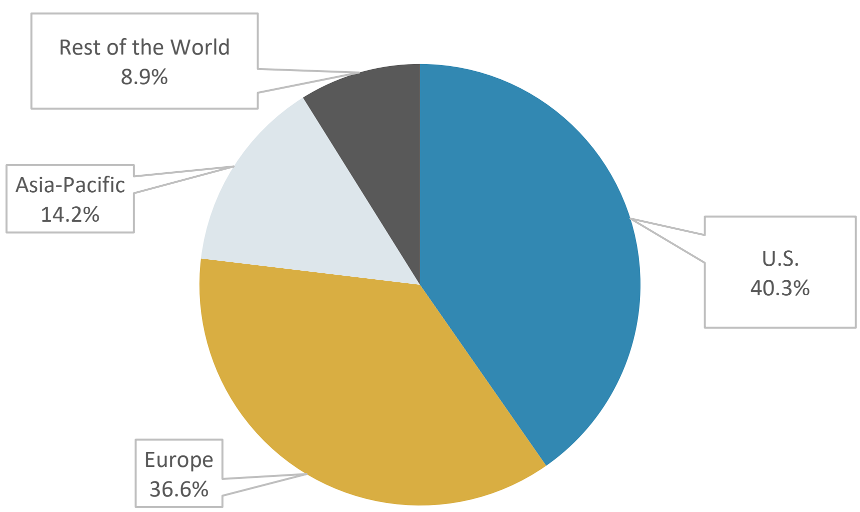
As summarized in the following table, this industry is estimated to expand at a CAGR of 4.5% during the next five years and reach $270.7 billion by 2025. The fastest growth is projected to occur in the Asia-Pacific region (with 6.5% CAGR) and in the Rest of the World (5.9% CAGR). However, the U.S and Europe are expected to continue to have the largest share of the market at 40.3% and 36.6% of the total, respectively, in 2025, as indicated in the next figure.

Table 29
Global Market for the Aerospace Industry, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	96.8	90.6	109.2	3.8
Europe	86.7	81.0	99.0	4.1
Asia-Pacific	29.8	28.0	38.4	6.5
Rest of the World	19.3	18.1	24.1	5.9
Total	232.6	217.7	270.7	4.5

Source: BCC Research

Figure 19
Estimated Global Market Shares of the Aerospace Industry, by Region, 2025
(%)



Source: BCC Research

Defense
Global defense spending is expected to grow at a CAGR between 2% and 3% during the next five years reaching an estimated $2.2 trillion by 2025, as governments allocate more resources to fight new threats and upgrade their defense systems. In addition to the U.S., other countries including Russia, China, and India are increasing their budgets to strengthen their national defense.

Within this industry, as previously discussed, advanced materials for extreme environments are being applied for fabrication of aircraft components, weapons, hypersonic and re-entry vehicles, and propulsion system. Two applications that are projected to provide a larger impact on the growth of the market for advanced materials for extreme environments during the next five years are thermal and environmental barrier coatings, and body and vehicle armor.

Body and Vehicle Armor
As shown in the following table and figure, sales of body and vehicle armor are forecast to grow from $12.3 billion in 2020 to $16.6 billion in 2025, corresponding to a 6.2% CAGR. Body armor includes personal protection products for military, law enforcement and civilian use. Vehicle armor includes products for land, air and marine vehicles.

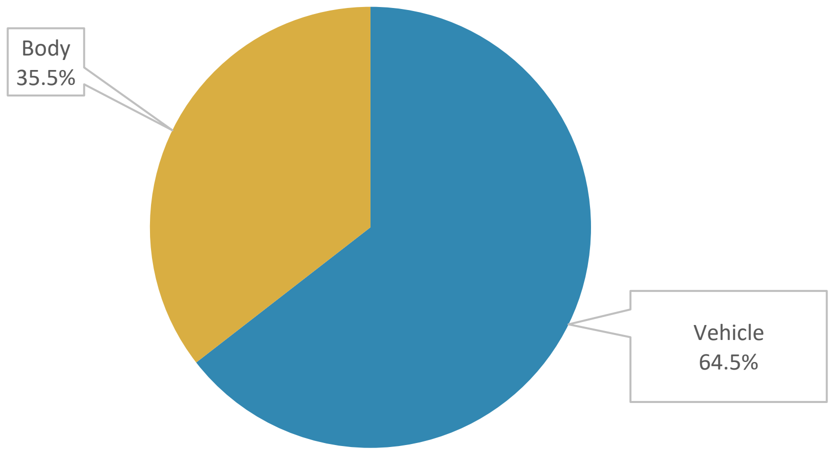
Vehicle armor, which represents the largest share of the market at an estimated 64.5% of the total in 2025, is projected to have moderately higher growth than body armor during the next five years.

Table 30
Global Market for Body and Vehicle Armor, by Type, Through 2025
($ Billions)

Type	2019	2020	2025	CAGR% 2020-2025
Vehicle	7.6	7.8	10.7	6.5
Body	4.4	4.5	5.9	5.6
Total	12.0	12.3	16.6	6.2

Source: BCC Research

Figure 20
Estimated Global Market Shares of Body and Vehicle Armor, by Type, 2025
(%)



Source: BCC Research

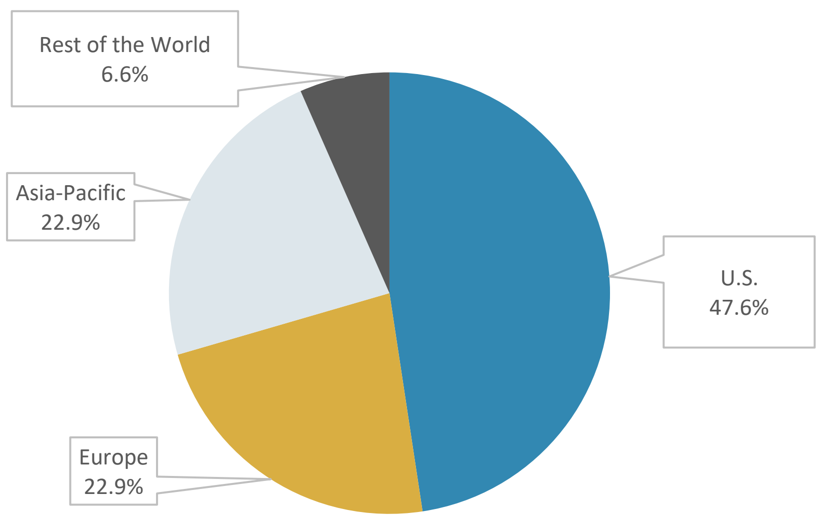
The next table indicates that the U.S. is the largest consumer of protection products with global estimated revenues of $7.9 billion in 2025, but the Asia-Pacific represents the fastest growing segment at a CAGR of 9.6% through 2025. By the end of the forecast period, the U.S. will account for a 47.6% share, followed by Europe and Asia-Pacific at 22.9% of the total, as displayed in the following figure.

Table 31
Global Market for Body and Vehicle Armor, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	5.8	6.0	7.9	5.7
Europe	3.1	3.1	3.8	4.2
Asia-Pacific	2.3	2.4	3.8	9.6
Rest of the World	0.8	0.8	1.1	6.6
Total	12.0	12.3	16.6	6.2

Source: BCC Research

Figure 21
Estimated Global Market Shares of Body and Vehicle Armor, by Region, 2025
(%)



Source: BCC Research

The most common material for vehicle and body protection are metals and alloys (e.g., steels), ceramics (including ceramic-based composites), and aramid (e.g., Kevlar). Other materials that are becoming popular, although their market is currently very small, are ultrahigh molecular weight polyethylene (UHMWPE) and fiberglass.

Ceramic materials are generally lighter than steel and can also be formed into complex shapes but are more expensive to produce. Also, large ceramic armor plates (used in vehicles) are characterized by lower multi-hit resistance compared to other materials. Advanced sintering technologies are becoming popular for production of nanostructured ceramic armors with exotic formulations (such as materials) aimed at improving their ballistic performance.

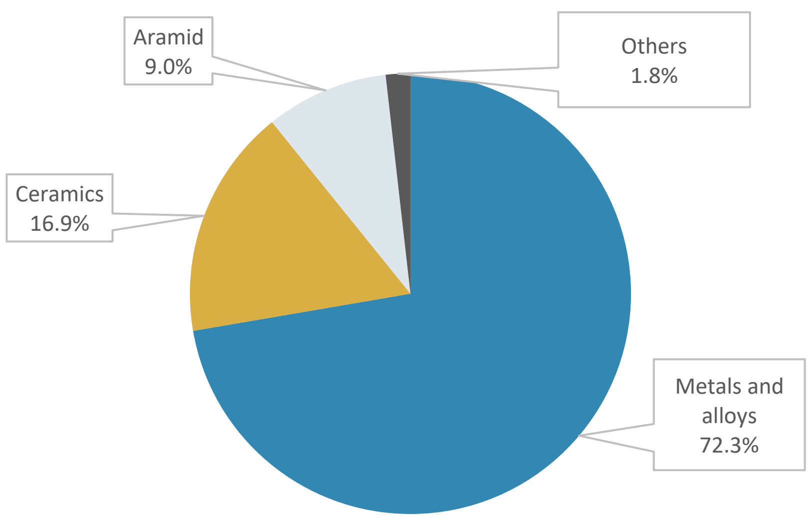
As shown in the next table, ceramic armor products (monolithic and composite) are estimated to be the fastest-growing segment of the armor market. Rising at a CAGR of 9.2% through 2025, global revenues will reach $2.8 billion by the end of the forecast period, or 16.9% of the total market, as illustrated in the following figure.

Table 32
Global Market for Body and Vehicle Armor, by Material, Through 2025
($ Billions)

Material	2019	2020	2025	CAGR% 2020-2025
Metals and alloys	9.0	9.2	12.0	5.5
Ceramics	1.7	1.8	2.8	9.2
Aramid	1.1	1.1	1.5	6.4
Others	0.2	0.2	0.3	8.4
Total	12.0	12.3	16.6	6.2

Source: BCC Research

Figure 22
Estimated Global Market Shares of Body and Vehicle Armor, by Material, 2025
(%)



Source: BCC Research

Thermal Barrier Coatings
Thermal barrier coatings (TBCs, also known as thermal protection systems or TPSs) are used in several other industries in addition to aerospace and defense, with the purpose of protecting the metal surface of specific components from excessive heat. TBCs enable these components to operate at temperatures higher than the melting temperature of the material being protected, allowing to improve the performances of these parts and their lifetime.

As shown in the table and figure below, aerospace and defense currently represent the largest consumers of thermal barrier coatings. This segment is projected to generate revenues of $5.8 billion in 2025, or 27.6% of the total market, registering a CAGR of 6.2% during the forecast period.

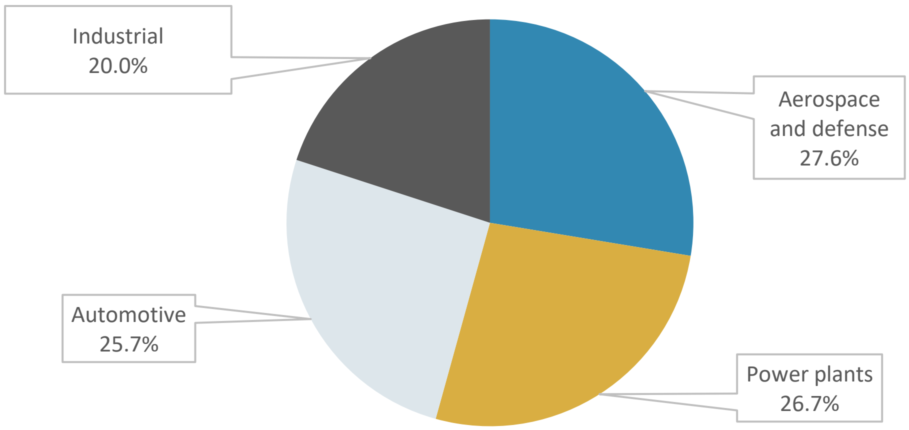
Power plants account for the second-largest share, at 26.7% in 2025, followed by the automotive sector (25.7%), and other applications in the industrial sector (20.0%).

Table 33
Global Market for Thermal Barrier Coatings, by Application Industry, Through 2025
($ Billions)

Application Industry	2019	2020	2025	CAGR% 2020-2025
Aerospace and defense	4.5	4.3	5.8	6.2
Power plants	4.2	4.0	5.6	7.0
Automotive	4.1	3.9	5.4	6.7
Industrial	3.0	2.9	4.2	7.7
Total	15.8	15.1	21.0	6.8

Source: BCC Research

Figure 23
Estimated Global Market Shares of Thermal Barrier Coatings, by Application Industry, 2025
(%)



Source: BCC Research

TBCs are made from metals and alloys, ceramics (including ceramic matrix composites) and polymeric materials. As displayed in the next table, metals and alloys account for the largest share of the market. This share is estimated to reach 45.7% of the total in 2025.

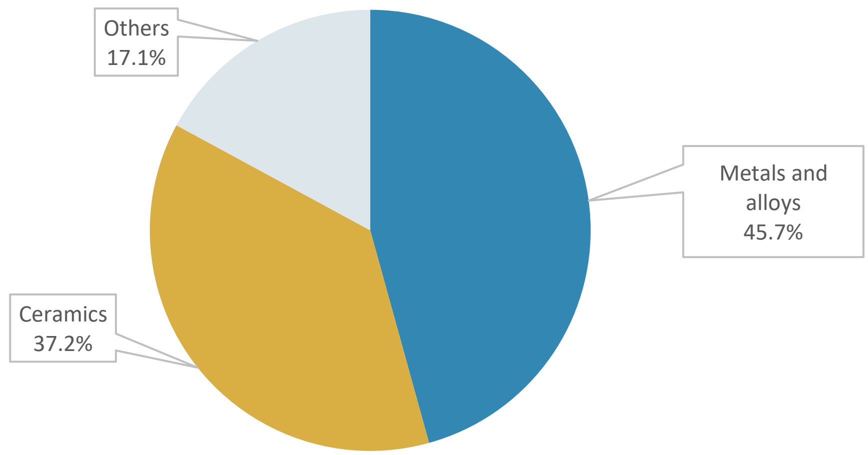
However, ceramic coatings are the fastest growing segment. Rising at a CAGR of 8.0% during the forecast period, these coatings are projected to be valued at $7.8 billion in 2025, corresponding to 37.2% of the total.

Table 34
Global Market for Thermal Barrier Coatings, by Material, Through 2025
($ Billions)

Material	2019	2020	2025	CAGR% 2020-2025
Metals and alloys	7.4	7.1	9.6	6.2
Ceramics	5.5	5.3	7.8	8.0
Others	2.9	2.7	3.6	5.9
Total	15.8	15.1	21.0	6.8

Source: BCC Research

Figure 24
Estimated Global Market Shares of Thermal Barrier Coatings, by Material, 2025
(%)



Source: BCC Research

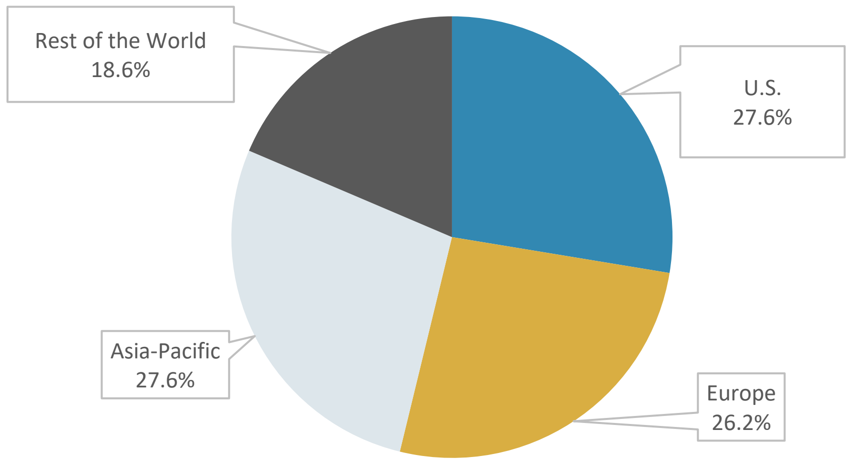
Geographically, the U.S. is currently the largest user of TBCs, but the Asia-Pacific region is experiencing the fastest growth. Expanding at a CAGR of 9.4% during the next five years, the Asia-Pacific region is forecast to generate the same revenues as the U.S. by 2025. With sales reaching $5.8 billion by the end of the forecast period, these two regions will reach a share of 27.6% of the global market in 2025, as summarized in the next table and figure.

Table 35
Global Market for Thermal Barrier Coatings, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	4.5	4.3	5.8	6.2
Asia-Pacific	3.8	3.7	5.8	9.4
Europe	4.4	4.1	5.5	6.1
Rest of the World	3.1	3.0	3.9	5.4
Total	15.8	15.1	21.0	6.8

Source: BCC Research

Figure 25
Estimated Global Market Shares of Thermal Barrier Coatings, by Region, 2025 (%)



Source: BCC Research

Energy

Currently, the most important applications of advanced materials for extreme environments within the energy sector are in the fabrication of gas turbines and parts for nuclear reactors. Secondary uses are in fuel cells, batteries, concentrated solar plants, and thermoelectric generation.

Gas Turbines

Gas turbines for electric power generation currently represent a $25.4 billion market. Due to the ongoing shift toward increasing use of renewable source of energy, this market is projected to have slow growth through 2025, resulting in global revenues of $29.0 billion by the end of the forecast period.

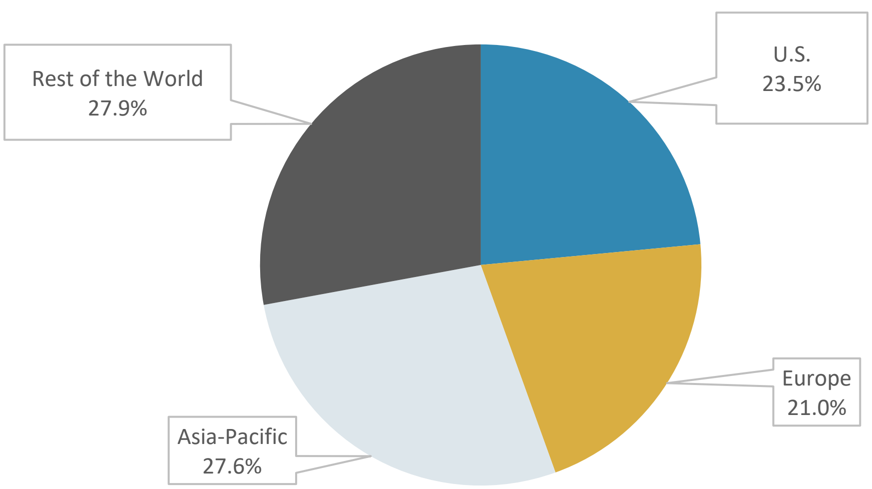
The rest of the world accounts for the largest share of the market at 27.9% of the total in 2025, whereas the Asia-Pacific region is projected to have the fastest expansion, with sales rising at a CAGR of 3.6% during the five-year period. These data are summarized in the following table and figure.

Table 36
Global Market for Gas Turbines, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	6.6	6.1	6.8	2.2
Asia-Pacific	7.3	6.7	8.0	3.6
Europe	6.2	5.6	6.1	1.7
Rest of the World	7.5	7.0	8.1	3.0
Total	27.6	25.4	29.0	2.7

Source: BCC Research

Figure 26
Estimated Global Market Shares of Gas Turbines, by Region, 2025
(%)



Source: BCC Research

Nuclear Plants

As shown in the next table, currently the Asia-Pacific region and the Rest of the World are heavily investing in the construction of new nuclear plants to support economic expansion and reduce their dependence from fossil fuel. However, according to data recently published by the World Nuclear Association (London, U.K.), building of new nuclear plants in these two regions should peak in 2021, resulting in much more moderate growth during the following four years.

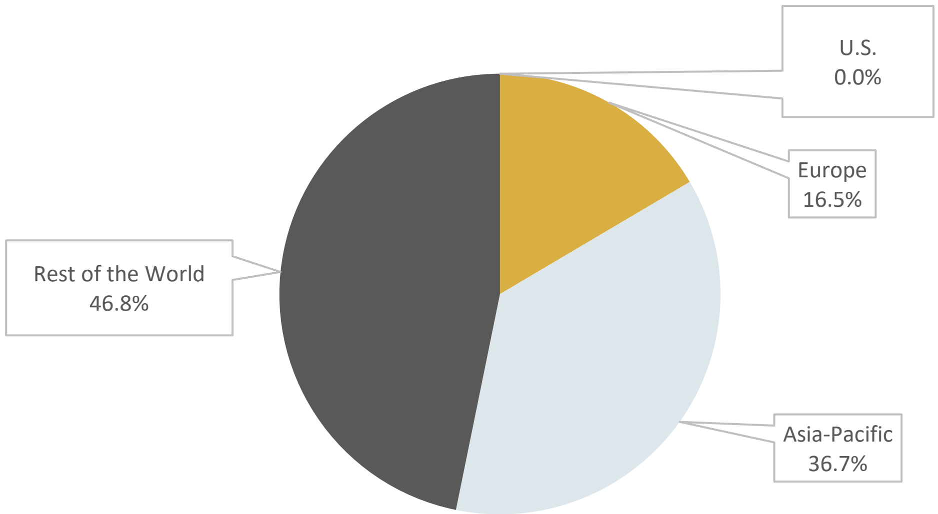
By the end of the 2025, the global market for nuclear plants is projected to reach $58.1 billion, registering a CAGR of 2.5% for the 2020-2025 period. In 2025, the Rest of the World will still account for the largest share of the market at 46.8% of the total, as indicated in the figure below.

Table 37
Global Market for Nuclear Plants, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	3.0	3.1	0.0	–
Asia-Pacific	19.1	20.1	21.3	1.2
Europe	2.7	2.8	9.6	27.9
Rest of the World	22.8	25.3	27.2	1.5
Total	47.6	51.3	58.1	2.5

Source: BCC Research

Figure 27
Estimated Global Market Shares of Nuclear Plants, by Region, 2025
(%)



Source: BCC Research

Concentrated Solar Power
Concentrated solar power is based on the utilization of mirrors to direct sunlight toward one single location where the solar energy is collected and converted first to heat and then to electric power through the use of steam turbines. advanced materials for extreme environments (in particular diborides) are finding application as high-temperature absorbers in solar energy receivers.

Driven by their low investment costs and relatively high efficiency, in addition to the ongoing need of decreasing CO_2 emissions and expanding reliance on renewable source of energy, the market for concentrated solar power is forecast to be characterized by healthy growth during the next five years.

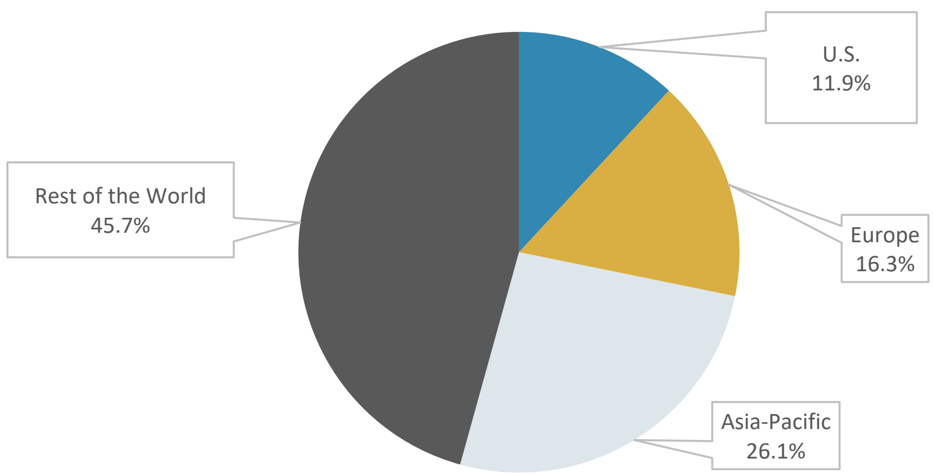
As shown in the next table and figure, concentrated solar power is expected to generate global revenues of $11.4 billion by 2025, corresponding to a CAGR of 10.5% during the forecast period. Geographically, concentrated solar power plants will be built primarily in the Rest of the World. In fact, concentrated solar power technology is particularly well suited for those areas that receive very intense sunlight, such as Africa, Middle East, Central America, and Northern Australia. The Rest of the World region will account for a share of 45.7% of the total in 2025 followed by the Asia-Pacific region (26.1%), which will experience the fastest growth with an 11.8% CAGR through 2025.

Table 38
Global Market for Concentrated Solar Power, by Region, Through 2025
($ Millions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	772	858	1,358	9.6
Asia-Pacific	1,511	1,710	2,992	11.8
Europe	1,106	1,219	1,860	8.8
Rest of the World	3,118	3,158	5,232	10.6
Total	6,507	6,945	11,442	10.5

Source: BCC Research

Figure 28
Estimated Global Market Shares of Concentrated Solar Power, by Region, 2025
(%)



Source: BCC Research

Fuel Cells

There are six main types of fuel cells: proton exchange membrane fuel cells (PEMFCs), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs), direct methanol fuel cells (DMFCs), and alkaline fuel cells (AFCs).

As shown in the table below, PEMFCs represent the largest share of the market. PEMFCs have multiple uses as stationary cells, in transportation, and for portable devices (e.g., consumer electronics, remote monitoring, and external battery chargers). By comparison, the main application for DMFCs is in portable devices, whereas all the remaining fuel cell types are mostly used in stationary power generation.

Growing at a CAGR of 17.9% during the next five years, PEMFCs are projected to generate global revenues of $5.7 billion in 2025, or 49.6% of the total (see next figure). MCFCs and SOFCs will follow with shares of 29.6% and 15.6%, respectively. The remaining types are estimated to account for a much smaller share at 5.2% of the total.

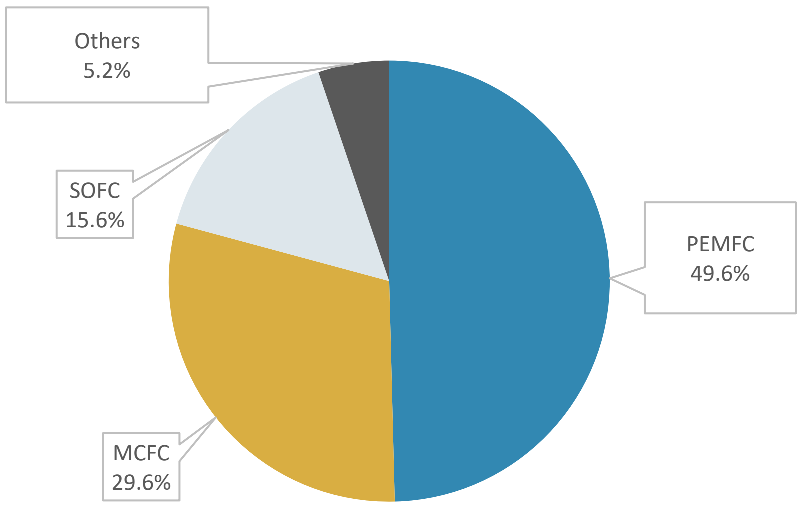
Fuel cells of all types are expected to be characterized by very healthy growth, with a CAGR of 18.1% through 2025, enabling the market to reach revenues of $11.5 billion by the end of the forecast period.

Table 39
Global Market for Fuel Cells, by Type, Through 2025
($ Billions)

Type	2019	2020	2025	CAGR% 2020-2025
PEMFC	2.6	2.5	5.7	17.9
MCFC	1.3	1.2	3.4	23.2
SOFC	1.0	1.0	1.8	12.5
Others	0.3	0.3	0.6	14.9
Total	5.2	5.0	11.5	18.1

Source: BCC Research

Figure 29
Estimated Global Market Shares of Fuel Cells, by Type, 2025
(%)



Source: BCC Research

Batteries

Batteries are typically divided into two groups: primary (non-rechargeable or disposable) and secondary (rechargeable). As shown in the next table, rechargeable batteries represent the largest market. Rechargeable batteries include six main types: lead acid, lithium-ion, nickel metal hydride (NiMH), nickel-cadmium (NiCd), reusable alkaline, and lithium-ion polymer.

Lithium-ion batteries (including both automotive batteries and batteries for portable devices) represent the fastest-growing segment of the rechargeable battery market, with a projected CAGR of 12.6% over the next five years. Advanced materials for extreme environments are of particular interest for fabrication of lithium-ion batteries with improved storage capacity retention and cycling stability, as well as tailored electromechanical behavior. In addition, advanced materials for extreme environments are receiving increasing attention for production of all-solid-state batteries.

Overall, the global battery market is estimated to expand at a 7.7% CAGR during the next five years and reach $156.9 billion by 2025.

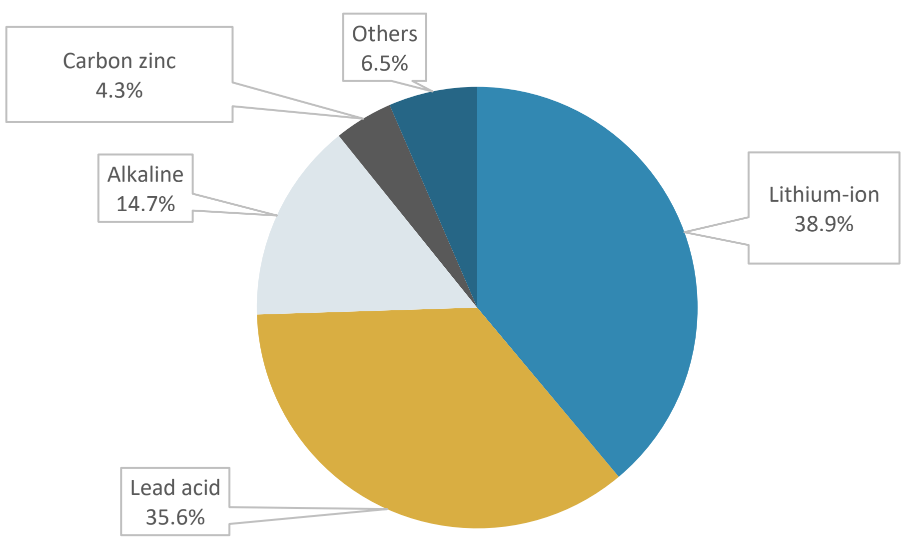
The next figure provides the 2025 sales breakdown for the main types of batteries.

Table 40
Global Market for Batteries, by Type, Through 2025
($ Billions)

Main Category	Type	2019	2020	2025	CAGR% 2020-2025
Primary	Alkaline	19.8	18.6	23.1	4.4
	Carbon zinc	6.0	5.6	6.7	3.7
	Lithium metal	1.9	1.8	2.1	3.1
	Others	1.4	1.3	1.5	2.9
	Subtotal Primary	29.1	27.3	33.4	4.1
Secondary	Lead acid	45.0	42.2	55.9	5.8
	Lithium-ion	35.8	33.7	61.0	12.6
	NiMH	2.5	2.4	3.0	4.6
	NiCd	1.6	1.5	1.8	3.7
	Others	1.4	1.3	1.8	6.7
	Subtotal Secondary	86.3	81.1	123.5	8.8
Total		115.4	108.4	156.9	7.7

Source: BCC Research

Figure 30
Estimated Global Market Shares of Batteries, by Type, 2025
(%)



Source: BCC Research

Other Technological Trends

In addition to the discussion on the growth of various industry sectors in which advanced materials for extreme environments find application, there are several technological trends that will impact sales of these materials during the next five years, as discussed below.

Lightweight Materials

There is growing interest in the utilization of advanced materials for extreme environments for lightweight components, such as sponges, foams, cellular structures, aerogels, that can be used to produce advanced structures for the aerospace, automotive, energy, and mechanical/chemical/metallurgical sectors.

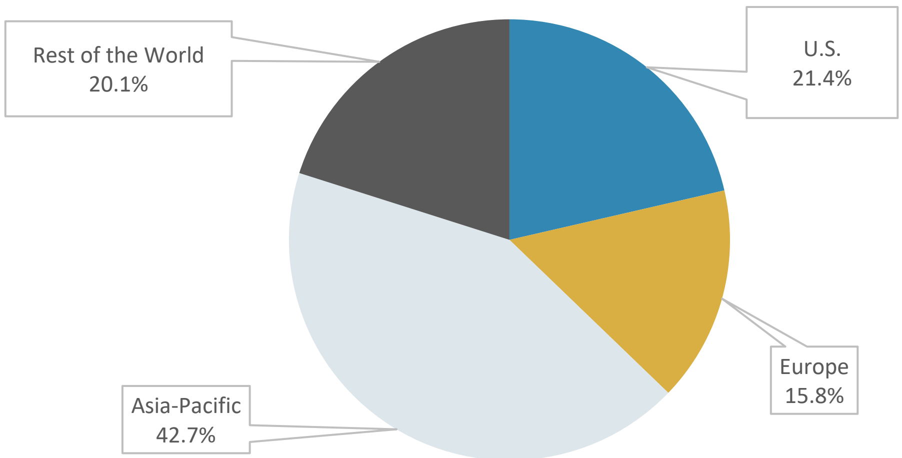
As shown in the next table and figure, the global market for lightweight materials (including metals and alloys, ceramic, polymers, and composites) is estimated to expand at a healthy CAGR of 8.7% through 2025 and reach revenues of $212.6 billion by the end of the forecast period. The Asia-Pacific region is the largest consumer of these materials and also the fastest-growing segment. In 2025, this region will account for a 42.7% share of the total, deriving from a CAGR of 11.1% during the 2020-2025 period.

Table 41
Global Market for Lightweight Materials, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	34.7	33.2	45.4	6.5
Asia-Pacific	54.9	53.6	90.8	11.1
Europe	26.0	25.5	33.7	5.7
Rest of the World	31.8	28.1	42.7	8.7
Total	147.4	140.4	212.6	8.7

Source: BCC Research

Figure 31
Estimated Global Market Shares of Lightweight Materials, by Region, 2025
(%)



Source: BCC Research

3D Printing

The introduction of 3D printing as a manufacturing technology is also expected to positively impact the future growth of the market for advanced materials for extreme environments. The possibility to create components with intricate geometry and tailored composition opens new paths in terms of performance and fields of application. Various types of composite materials with complex 3D architecture and unusual shapes are also becoming possible due to additive manufacturing.

The next table and figure show the regional breakdown of revenues for 3D printing of technical ceramics through 2025.

The U.S. is the leader in manufacturing and consumption of 3D printed technical ceramics during the next five years. In this region, revenues are forecast to grow at a 28.2% CAGR through 2025 and reach $391 million by 2025, corresponding to a 51.2% share.

In Europe, sales related to 3D printing of technical ceramics are forecast to increase at a CAGR of 26.1% during the period 2020 through 2025, generating revenues of $255 million in 2025, equal to a 33.4% share of the total market.

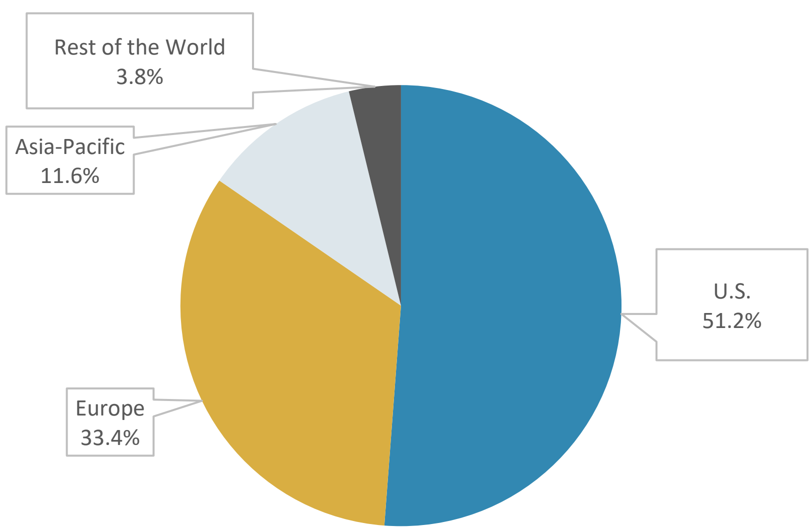
In the Asia-Pacific region, revenues are projected to be valued at $89 million in 2025 (an 11.6% share), corresponding to a CAGR of 19.8% during the next five years, whereas in the Rest of the World, the market for 3D printing of technical ceramics will grow at a CAGR of 19.3% during the forecast period and reach $29 million by the end of 2025, corresponding to 3.8% of the total market.

Table 42
Global Market for 3D Printing of Technical Ceramics, by Region, Through 2025
($ Millions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	119	113	391	28.2
Europe	86	80	255	26.1
Asia-Pacific	41	36	89	19.8
Rest of the World	13	12	29	19.3
Total	259	241	764	26.0

Source: BCC Research

Figure 32
Estimated Global Market Shares of 3D Printing of Technical Ceramics,
by Region, 2025
(%)



Source: BCC Research

Artificial Intelligence

Artificial intelligence (AI) is a term used to identify a scientific field that covers the creation of machines aimed at reproducing wholly or in part the intelligent behavior of human beings. These machines include computers, sensors, robots, and hypersmart devices. The ultimate purpose of artificial intelligence is to create smart machines that, through the steps of learning, reasoning, and self-correcting, will eventually be able to make decisions, solve problems, and act as human beings.

The concept of artificial intelligence is in continuous evolution. In fact, once the use of machines with specific smart features becomes widespread, new systems with even more advanced capabilities are developed. By enhancing equipment functionality and productivity, AI is revolutionizing virtually every sector, from research and development to manufacturing and services.

AI is also being applied in the development of innovative materials. In particular, AI is being exploited in the fabrication of advanced material components for extreme environments with predictable properties and optimized features.

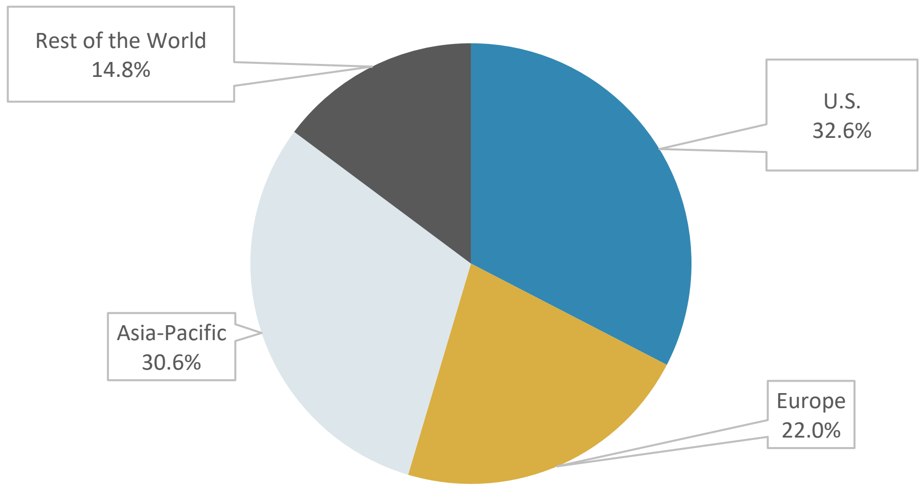
As indicated in the table and figure below, the AI market, which includes hardware, software and services, is forecast to rise at a very rapid rate, with a 51.9% CAGR through 2025. Global revenues are projected to reach $196.7 billion in 2025, up from $24.3 billion in 2020. Currently the U.S. represents the largest segment, but the Asia-Pacific region is the fastest-growing market. By the end of the five-year period, the Asia-Pacific region will generate revenues of $60.3 billion, accounting for 30.6% of the total.

Table 43
Global Market for Artificial Intelligence, by Region, Through 2025
($ Billions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	5.7	7.9	64.1	52.0
Asia-Pacific	4.9	6.9	60.3	54.3
Europe	4.1	5.6	43.2	50.5
Rest of the World	2.9	3.9	29.1	49.5
Total	17.6	24.3	196.7	51.9

Source: BCC Research

Figure 33
Estimated Global Market Shares of Artificial Intelligence, by Region, 2025
(%)



Source: BCC Research

Emerging Applications in the Energy Sector

Market growth of advanced materials for extreme environments will also be impacted by emerging applications, such as thermoelectric devices and supercapacitors. Hafnium and titanium boride composites are being introduced as high-temperature thermoelectric materials, whereas transition metal borides, carbides and nitrides are being employed as enhanced electrode materials in high-energy density supercapacitors.

Thermoelectric Devices

Thermoelectric (TE) devices convert thermal energy into electric power (or vice versa) based on the Peltier-Seebeck effect. There is growing interest in the use of thermoelectric devices for energy harvesting, such as devices that convert energy produced by human beings, in the form of body heat or kinetic energy from motion, into electrical power for wearable devices, biosensors, and medical implants. Other examples are represented by the transformation of heat created by combustion engines or manufacturing processes into electricity.

As shown in the table and figure below, revenues for thermoelectric devices are projected to rise from $316 million in 2020 to $758 million in 2025, corresponding to a CAGR of 19.1% during the next five years.

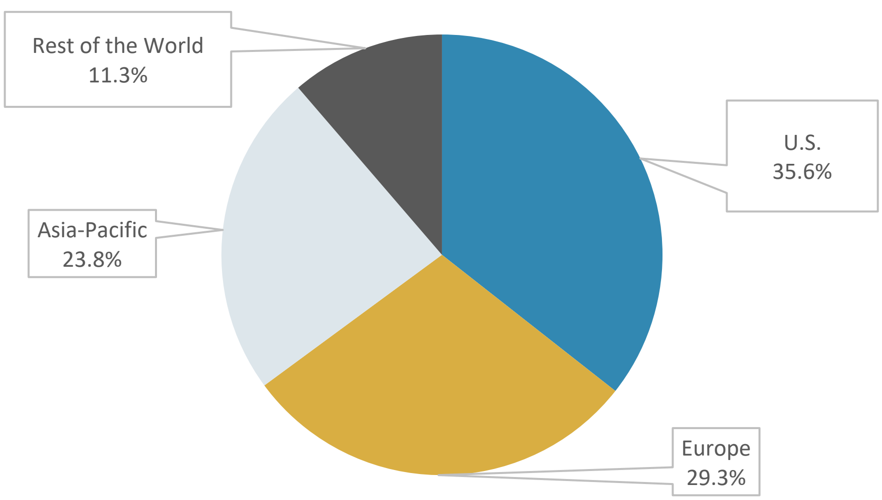
The U.S. is the largest user of these devices with revenues estimated to reach $270 million in 2025, corresponding to 35.6% of the total.

Table 44
Global Market for Thermoelectric Devices, by Region, Through 2025
($ Millions)

Region	2019	2020	2025	CAGR% 2020-2025
U.S.	127	116	270	18.4
Europe	105	96	222	18.3
Asia-Pacific	75	71	180	20.4
Rest of the World	34	33	86	21.1
Total	341	316	758	19.1

Source: BCC Research

Figure 34
Estimated Global Market Shares of Thermoelectric Devices, by Region, 2025
(%)



Source: BCC Research

Supercapacitors
Supercapacitors (also also known as ultracapacitors, supercondensers, pseudocapacitors, electrical double-layer capacitors, electrochemical double-layer capacitors, or ELDCs) are devices capable of storing and releasing energy. They are characterized by a very high capacitance value, measurable from microfarads to kilofarads.

Although the most popular type is based on carbon electrodes, other supercapacitors are commercially available with polymeric or ceramic electrodes, in asymmetric configurations, or in the form of hybrid devices. They also come in rigid and flexible design. Supercapacitors have current and potential use in the following sectors: electronics, energy, medical, sensors and instrumentation, and transportation.

As shown in the table and figure below, the global market for both rigid and flexible supercapacitors is estimated to be valued at $1.8 billion by the end of 2020 and forecast to grow at a very healthy CAGR of 20.2% through 2025, reaching global revenues of $4.4 billion by 2025.

Revenue growth for supercapacitors is being driven primarily by the utilization of these devices in the transportation sector, due to the rapid growth of the electric vehicle market. The transportation sector is estimated to account for 52.5% of all revenues in 2025.

The electronics sector accounts for the second-largest share of the market at an estimated 32.2% of the total in 2025. Within this sector, supercapacitors are primarily used for manufacturing various portable and handheld devices, such as mobile phones, tablet and notebook computers, digital cameras and other audio/video products.

Continued expansion of the renewable energy and smart grid sectors will drive rapid growth of supercapacitors for energy applications, bringing revenues to reach a 15.1% share of the total by the end of the forecast period. All the remaining applications, combined, will represent a negligible share at 0.2% of the total market in 2025.

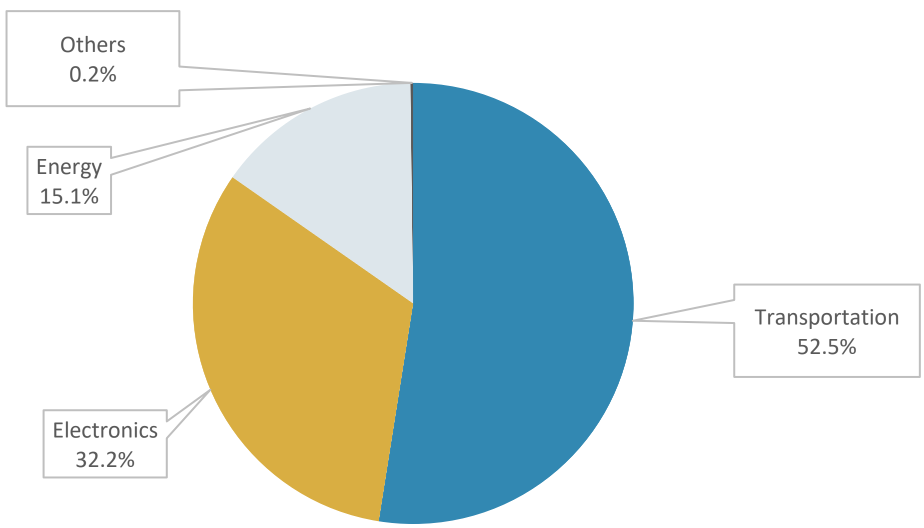
Supercapacitors are growing in importance as components to store and supply energy in electric vehicles, electronic devices, wind and photovoltaic power generators, power grids, and cordless instruments and sensors. These applications will require even higher energy density and power density from the next generation of supercapacitors. In addition, the emergence of wearable and flexible electronics is leading to significant demand for flexible EDLCs. TiC composite electrodes are being introduced for fabrication of flexible supercapacitors with superior electrochemical performance.

Table 45
Global Market for Supercapacitors, by Application Industry, Through 2025
($ Millions)

Application Industry	2019	2020	2025	CAGR% 2020-2025
Transportation	748	741	2,307	25.5
Electronics	805	726	1,416	14.3
Energy	303	284	664	18.5
Others	5	5	10.0	14.9
Total	1,861	1,756	4,397	20.2

Source: BCC Research

Figure 35
Estimated Global Market Shares of Supercapacitors, by Application Industry, 2025
(%)



Source: BCC Research

Regional Trends

More than 40% of all companies involved in the development and fabrication of advanced ceramic materials for extreme environments are located in the U.S., approximately 25% are placed in Europe, while the remaining 35% are distributed between the Asia-Pacific region and the Rest of the World. The market is formed by players of different sizes that serve both national and international markets.

Currently, the U.S. is the leading producer and consumer of advanced materials for extreme environments. This leadership derives from the U.S. strength in metalworking, machining, and tools manufacturing. These activities are driven by very large industries such as aerospace, defense, and transportation (cars, commercial vehicles and trucks, and marine).

To fight fierce competition in these fields, U.S. organizations are also investing in advanced materials for extreme environments-related R&D, focusing primarily on UHTC formulations. Among all the types of advanced materials for extreme environments, UHTCs are the most commonly used in a variety of applications, even though they still require composition and process optimization.

Considering all these factors, the U.S. is expected to remain the major developer, producer, and consumer of advanced materials for extreme environments during the next five years.

The Asia-Pacific region is projected to continue to be the second-largest consumer of advanced ceramic materials for extreme environments. At the present time, this region is a net importer of advanced products for extreme environments. With so many manufacturing activities being moved to China due to its lower labor costs and less stringent environmental regulations, this country is rapidly becoming a major competitor of the U.S. in the development of new technologies. As a result, consumption and production of advanced materials for extreme environments in the Asia-Pacific region will continue to grow at a healthy pace in the near future.

During the next five years, Europe will remain the third-largest consumer of advanced materials for extreme environments and a net exporter, considering the significant number of players in this field. In this region, demand for advanced materials for extreme environments will be determined mainly by applications in the mechanical/chemical sector and in aerospace.

In the Rest of the World, consumption of advanced materials for extreme environments will be positively affected by a generally healthy mechanical industry, although demand for these products is forecast to be at a relatively low level compared with more industrialized regions of the world.

Market Forecast

Based on the discussion covering industry growth and technological trends, BCC Research has developed a market forecast for advanced ceramic materials for extreme environments for the period 2020 through 2025.

Market by Material Group

The table below provides forecast revenues for advanced ceramic materials for extreme environments for the next five years by material group. The following figure shows the relative breakdown for 2025.

UHTCs will remain the most popular products. Sales of these products are expected to experience moderate growth, with a CAGR of 5.7% during the forecast period. They will reach $3.8 billion by 2025, corresponding to a share of 98.6% of the total. Market growth will be driven by increasing demand across all fields of application.

The market for MAX phase ceramics is projected to rise at a healthier CAGR of 6.4% through 2025. These products will generate global sales of $49 million by 2025, corresponding to 1.3% of the total market.

HECs are estimated to leave the development stage during the next five years and generate revenues of approximately $5 million in 2025, corresponding to a share of 0.1% of the total.

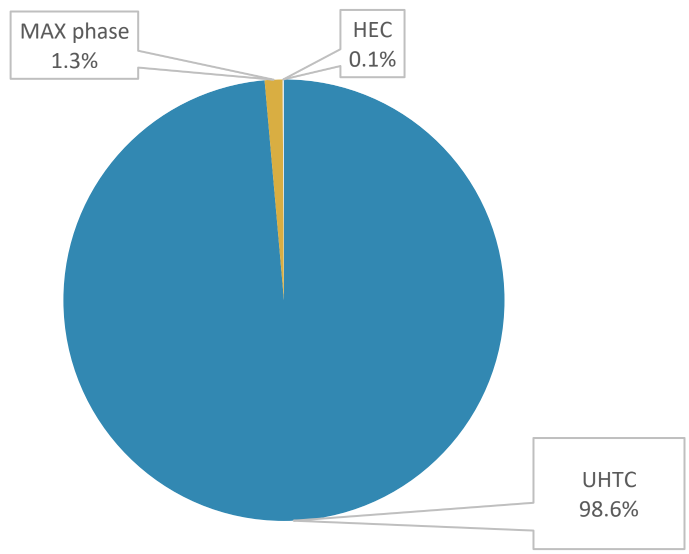
Due to general moderate growth of all these segments, the market for advanced materials for extreme environments will expand at a CAGR of 5.7 through 2025, reaching $3.8 billion by the end of the forecast period.

Table 46
Global Market for Advanced Ceramic Materials for Extreme Environments, by Material Group, Through 2025
($ Millions)

Material Group	2020	2025	CAGR% 2020-2025
UHTC	2,848	3,759	5.7
MAX phase	36	49	6.4
HEC	–	5	N.A.
Total	2,884	3,813	5.7

Source: BCC Research

Figure 36
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Material Group, 2025
(%)



Source: BCC Research

Market by Composition

As shown in the next table and figure summarize, by 2025, nitride-based advanced materials for extreme environments are predicted to generate global revenues of $3.3 billion (or 85.7% of the total), corresponding to a CAGR of 5.8% during the forecast period.

Boride-based advanced materials for extreme environments, however, will be characterized by the fastest growth with a CAGR of 6.2%. By 2025, sales of these ceramics are projected to reach $295 million, representing a 7.7% of the total.

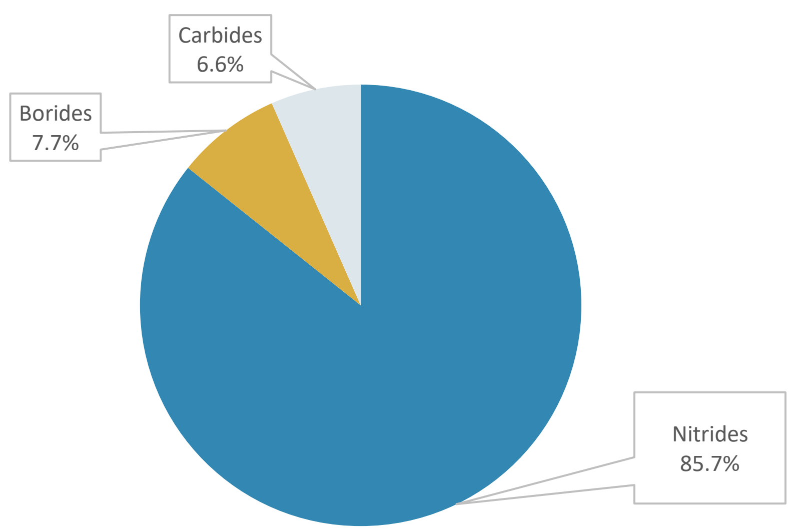
Carbide-based advanced materials for extreme environments are forecast to become a more significant share of the total market at 6.6% of the total. Expanding at a CAGR of 5.1% during the forecast period, this segment will be valued at $251 million in 2025.

Table 47
Global Market for Advanced Ceramic Materials for Extreme Environments, by Composition, Through 2025
($ Millions)

Composition	2020	2025	CAGR% 2020-2025
Nitrides	2,470	3,267	5.8
Borides	218	295	6.2
Carbides	196	251	5.1
Total	2,884	3,813	5.7

Source: BCC Research

Figure 37
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Composition, 2025
(%)



Source: BCC Research

Market by Microstructure

As shown in the table and figure below, by 2025, monolithic advanced materials for extreme environments are predicted to generate global revenues of $977 million (or 25.6% of the total), corresponding to a CAGR of 5.2% during the forecast period.

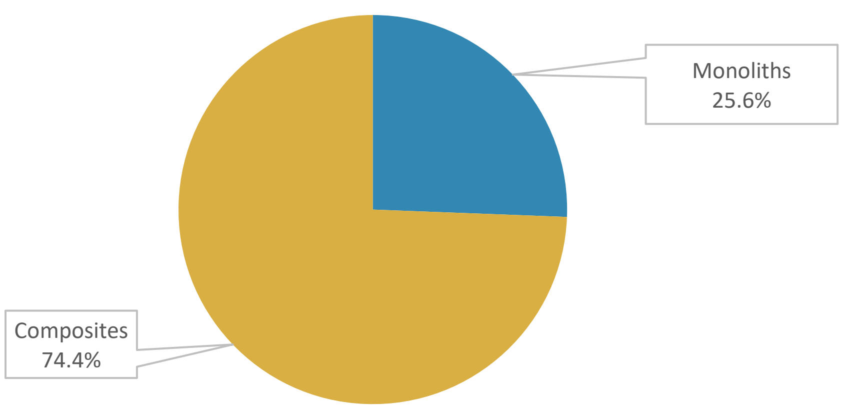
Composites will be characterized by a faster growth with a CAGR of 6.0%. By 2025, sales of these products are projected to reach $2.8 billion, representing a 74.4% of the total.

Table 48
Global Market for Advanced Ceramic Materials for Extreme Environments, by Microstructure, Through 2025
($ Millions)

Microstructure	2020	2025	CAGR% 2020-2025
Composites	2,124	2,836	6.0
Monoliths	760	977	5.2
Total	2,884	3,813	5.7

Source: BCC Research

Figure 38
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Microstructure, 2025
(%)



Source: BCC Research

Market by Configuration

The next table and figure summarize the growth forecast for advanced materials for extreme environments by configuration. By 2025, bulk advanced materials for extreme environments are predicted to generate global revenues of $3.6 billion (or 95.2% of the total), corresponding to a CAGR of 5.8% during the forecast period.

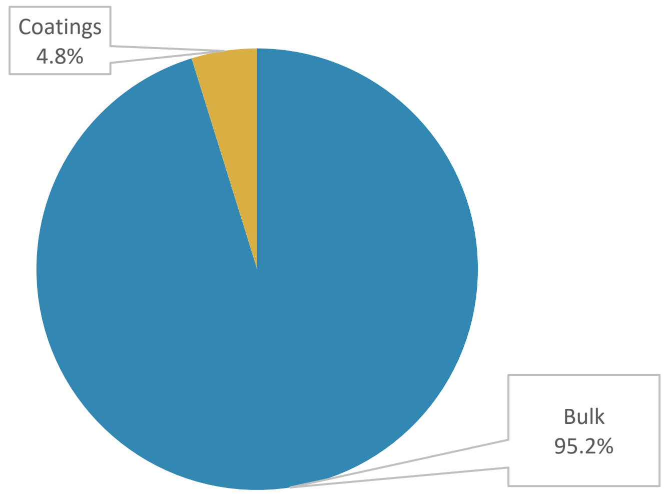
Coatings will be expanding at CAGR of 5.1% through 2025 reaching $183 million by the end of the considered period, corresponding to a 4.8% share of the total market.

Table 49
Global Market for Advanced Ceramic Materials for Extreme Environments, by Configuration, Through 2025
($ Millions)

Configuration	2020	2025	CAGR% 2020-2025
Bulk	2,741	3,630	5.8
Coatings	143	183	5.1
Total	2,884	3,813	5.7

Source: BCC Research

Figure 39
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Configuration, 2025
(%)



Source: BCC Research

Market by Application Industry

The next table and figure provide the sales breakdown for advanced ceramic materials for extreme environments by application for the 2020-2025 period.

The mechanical/chemical/metallurgical sector is forecast to remain the leading field of application for advanced materials for extreme environments in 2025, with revenues accounting for 92.3% of the total market. This segment will expand at a CAGR of 5.6% during the next five years and generate global revenues of $3.5 billion by the end of forecast period.

Advanced materials for extreme environments for aerospace and defense are forecast to grow at a healthier CAGR of 7.2% during the 2020-2025 period, resulting in total sales of $217 million in 2025, or 5.7% of the total.

Sales of advanced materials for extreme environments for energy applications will amount to $70 million in 2025 (1.8% of the total), corresponding to a CAGR of 6.5% during the next five years.

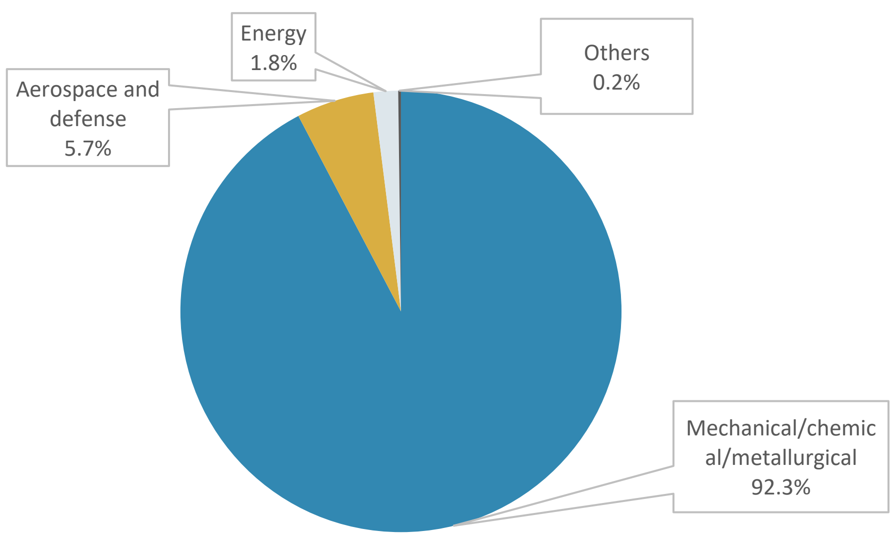
Expanding at a CAGR of 5.9% during the five-year period, advanced materials for extreme environments for other applications will generate revenues of $8 million, representing a 0.2% share by 2025.

Table 50
Global Market for Advanced Ceramic Materials for Extreme Environments, by Application Industry, Through 2025
($ Millions)

Application Industry	2020	2025	CAGR% 2020-2025
Mechanical/chemical/metallurgical	2,674	3,518	5.6
Aerospace and defense	153	217	7.2
Energy	51	70	6.5
Others	6	8	5.9
Total	2,884	3,813	5.7

Source: BCC Research

Figure 40
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Application Industry, 2025
(%)



Source: BCC Research

Market by Region

The table below provides the regional breakdown of revenues for advanced ceramic materials for extreme environments during the period 2020 through 2025. The next figure shows the repartition of sales among different regions in 2025.

U.S. revenues deriving from sales of advanced materials for extreme environments are forecast to grow at a 5.9% CAGR through 2025 and reach nearly $1.5 billion by 2025, corresponding to a 38.6% share

In Europe, sales of advanced materials for extreme environments are projected to increase at a CAGR of 5.4% during the period 2020 through 2025, generating revenues of $783 million by 2025, equal to a 20.6% share of the total market.

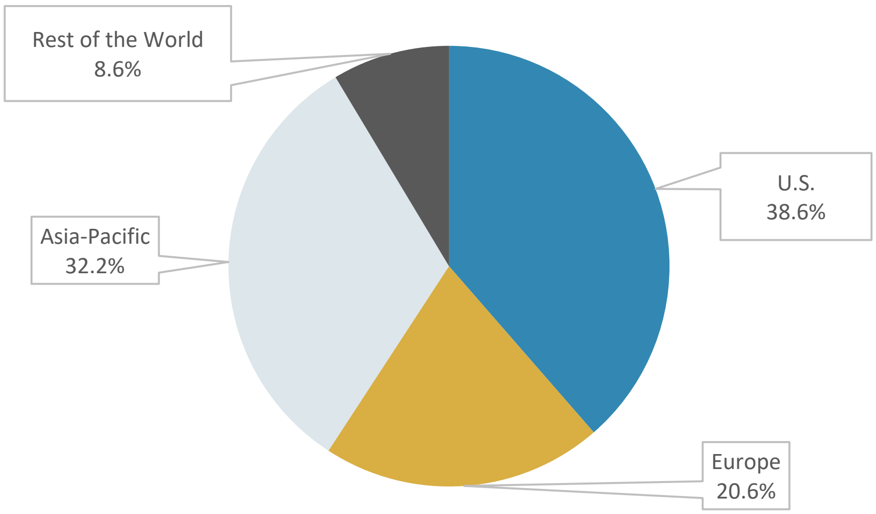
In the Asia-Pacific region, these products are forecast to generate sales of $1.2 billion in 2025 (a 32.2% share), corresponding to a CAGR of 5.6% during the next five years. In the Rest of the World, a CAGR of 6.2% is projected, leading to global sales of $329 million by 2025, or 8.6% of the total market.

Table 51
Global Market for Advanced Ceramic Materials for Extreme Environments, by Region, Through 2025
($ Millions)

Region	2020	2025	CAGR% 2020-2025
U.S.	1,105	1,473	5.9
Asia-Pacific	934	1,228	5.6
Europe	601	783	5.4
Rest of the World	244	329	6.2
Total	2,884	3,813	5.7

Source: BCC Research

Figure 41
Estimated Global Market Shares of Advanced Ceramic Materials for Extreme Environments, by Region, 2025
(%)



Source: BCC Research

Chapter 6

Global Industry Structure and Company Profiles

Chapter 6: Global Industry Structure and Company Profiles

In this section, BCC Research analyzes the current structure of the market for advanced materials for extreme environments through an evaluation of its key players. This is achieved by:

- Highlighting the leading suppliers of advanced materials for extreme environments and products based on these materials.
- Providing a brief description of pertinent products offered by each company.
- Determining the geographical distribution of all the leading producers.
- Indicating other relevant industry players, including suppliers of materials and fabrication equipment, developers of new technologies, and future market participants.
- Providing detailed profiles of the top players. These profiles will offer a more comprehensive description of the breadth of activities within this market and indicate the range of products made by each manufacturer.

Leading Manufacturers of Advanced Materials and Products for Extreme Environments

BCC Research conducts its global industry analysis by first describing the leading manufacturers of advanced materials and products for extreme environments. They are identified by company name, location, and type of product.

These companies are listed in alphabetical order in the next table. The list is not intended to be comprehensive but does include all the major players.

Table 52
Leading Manufacturers of Advanced Materials and Products for Extreme Environments, 2020

Company	Headquarters	Type of Material
3M	St. Paul, MN	UHTC monoliths and composites
Able Target	Jiangsu, China	UHTC sputtering targets
AC Technologies	Yonkers, NY	UHTCs
Advanced Ceramic Materials	Lake Forest, CA	UHTCs
Advanced Ceramics Manufacturing	Tucson, AZ	UHTC monoliths and composites
Ansaldo Energia	Genoa, Italy	MAX phase ceramics
Aremco Products	Valley Cottage, NY	UHTC monoliths and composites
ArianeGroup	Les Mureaux, France	UHTC composites
Atlantic Equipment Engineers	Upper Saddle River, NJ	UHTC sputtering targets and other shapes
BrahMos Aerospace	New Delhi, India	UHTC composites
Ceramdis	Elsau, Switzerland	UHTCs
CeramTec	Plochingen, Germany	UHTC composites
CoorsTek	Golden, CO	UHTCs
Denka	Tokyo, Japan	UHTCs
Element Six	Didcot, U.K.	UHTC composites
Funik Ultrahard Material	Zhengzhou, China	UHTC composites
GE Aviation	Cincinnati, OH	UHTC monoliths and composites
Goodfellow	Coraopolis, PA	UHTC sheets and sputtering targets
Haldor Topsoe	Lyngby, Denmark	MAX phase ceramics
Halliburton Energy Services	Houston, TX	UHTCs
Henze BNP	Lauben, Germany	UHTC monoliths and composites
Honsin Advanced Ceramics	Dahan, China	UHTC monoliths and composites
Hyperion	Worthington, OH	UHTC composites
Kennametal	Fort Mill, SC	UHTC monoliths and composites
Kyocera	Kyoto-shi, Japan	UHTC composites
Matech	Westlake Village, CA	UHTC composites
Materion	Mayfield Heights, OH	UHTC sputtering targets and other shapes
Momentive Performance Materials	Waterford, NY	UHTC monoliths and composites
Morgan Advanced Materials	Rudgby, U.K.	UHTCs
MSE Supplies	Tucson, AZ	UHTC sputtering targets
NASA Ames	Mountain View, CA	UHTC monoliths and composites
NASA Glenn Research Center	Cleveland, OH	MAX phases ceramics
NSWC Carderock Division	West Bethesda, MD	UHTCs
Ortech Advanced Ceramics	Sacramento, CA	UHTCs

Company	Headquarters	Type of Material
PAM-Xiamen	Xiamen, China	UHTC monoliths and coatings
PENSC	Zibo City, China	UHTC monoliths and composites
Plansee	Reutte, Austria	UHTC sputtering targets
Raytheon Technologies	Waltham, MA	MAX phase ceramics
Reade Advanced Ceramics	Riverside, RI	UHTC parts and sputtering targets, monoliths and composites
Rolls-Royce	London, U.K.	MAX phase ceramics
Safran	Paris, France	UHTC composites and MAX phase ceramics
Saint Gobain	Courbevoie, France	UHTC monoliths and composites
Sandvik	Stockholm, France	UHTC monoliths and composites and MAX phase ceramics
Shanghai Kessen Ceramics	Shanghai, China	UHTC parts and sputtering targets
Shin-Etsu Chemical	Tokyo, Japan	UHTCs
Showa Denko	Tokyo Japan	UHTC composites
Siemens	Munich, Germany	MAX phase ceramics
Stanford Advanced Materials	Lake Forest, CA	UHTC sputtering targets
Sumitomo Electric Industries	Osaka, Japan	UHTC monoliths and composites
T.Q. Abrasive Machining	Santa Ana, CA	UHTCs
Tomei Diamond	Tokyo, Japan	UHTC composites
Tungaloy	Iwaki-city, Japan	UHTC composites
Ultramet	Pacoima, CA	UHTC composites and coatings
Wuxi Sundi Precision Tools	Wuxi, China	UHTC composites
Xiamen Innovacera Advanced Materials	Xiamen, China	UHTC monoliths and composites
Xiamen Unipretec Ceramic Technology	Xiamen, China	UHTC monoliths and composites
Zhengzhou Berlt Hard Material	Zhengzhou, China	UHTC composites
Zibo Deming Advanced Materials	Shandong, China	UHTC monolithic and composites
Zibo Jonye Ceramic Technologies	Shandong, China	UHTC monoliths, composites and coatings
Zibo Sinyo Nitride Materials	Zibo City, China	UHTC monolithic and composites

Source: BCC Research

Of the 60 leading companies, 25 (or 41.7% of the total) are headquartered in the U.S., 14 in Europe (23.3%), 20 (33.3%) in the Asia-Pacific region, and 1 (1.7%) in the Rest of the World.

Distribution of Leading Manufacturers by Type of Material and Region

In the next tables, the leading players are sorted in three groups, corresponding to the main types of advanced materials and products for extreme environments that are currently commercialized: UHTC monoliths and coatings; UHTC composites; MAX phase ceramics.

The first group includes producers of UHTC monoliths and coatings, with a total of 40 players. As indicated in the last table below, most of these producers are headquartered in the U.S. (52.5% of the total), followed by the Asia-Pacific region (32.5%), and Europe (15.0%).

Table 53
Leading Manufacturers of UHTC Monoliths and Coatings, 2020

Company	Headquarters
3M	St. Paul, MN
Able Target	Jiangsu, China
AC Technologies	Yonkers, NY
Advanced Ceramic Materials	Lake Forest, CA
Advanced Ceramics Manufacturing	Tucson, AZ
Aremco Products	Valley Cottage, NY
Atlantic Equipment Engineers	Upper Saddle River, NJ
Ceramdis	Elsau, Switzerland
CoorsTek	Golden, CO
Denka	Tokyo, Japan
GE Aviation	Cincinnati, OH
Goodfellow	Coraopolis, PA
Halliburton Energy Services	Houston, TX
Henze BNP	Lauben, Germany
Honsin Advanced Ceramics	Dahan, China
Kennametal	Fort Mill, SC
Materion	Mayfield Heights, OH
Momentive Performance Materials	Waterford, NY
Morgan Advanced Materials	Rudgby, U.K.
MSE Supplies	Tucson, AZ
NASA Ames	Mountain View, CA
NSWC Carderock Division	West Bethesda, MD
Ortech Advanced Ceramics	Sacramento, CA
PAM-Xiamen	Xiamen, China
PENSC	Zibo City, China
Plansee	Reutte, Austria
Reade Advanced Ceramics	Riverside, RI
Saint Gobain	Courbevoie, France
Sandvik	Stockholm, France
Shanghai Kessen Ceramics	Shanghai, China

Company	Headquarters
Shin-Etsu Chemical	Tokyo, Japan
Stanford Advanced Materials	Lake Forest, CA
Sumitomo Electric Industries	Osaka, Japan
T.Q. Abrasive Machining	Santa Ana, CA
Ultramet	Pacoima, CA
Xiamen Innovacera Advanced Materials	Xiamen, China
Xiamen Unipretec Ceramic Technology	Xiamen, China
Zibo Deming Advanced Materials	Shandong, China
Zibo Jonye Ceramic Technologies	Shandong, China
Zibo Sinyo Nitride Materials	Zibo City, China

Source: BCC Research

The second group includes suppliers of UHTC composites. A total of 34 players were found, mostly headquartered in the Asia-Pacific Region (44.1%), followed by the U.S. (32.4%), Europe (20.6%) and the Rest of the World (2.9%).

Table 54
Leading Manufacturers of UHTC Composites, 2020

Company	Headquarters
3M	St. Paul, MN
Advanced Ceramics Manufacturing	Tucson, AZ
Aremco Products	Valley Cottage, NY
ArianeGroup	Les Mureaux, France
BrahMos Aerospace	New Delhi, India
CeramTec	Plochingen, Germany
Element Six	Didcot, U.K.
Funik Ultrahard Material	Zhengzhou, China
GE Aviation	Cincinnati, OH
Henze BNP	Lauben, Germany
Honsin Advanced Ceramics	Dahan, China
Hyperion	Worthington, OH
Kennametal	Fort Mill, SC
Kyocera	Kyoto-shi, Japan
Matech	Westlake Village, CA
Momentive Performance Materials	Waterford, NY
NASA Ames	Mountain View, CA
PENSC	Zibo City, China
Reade Advanced Ceramics	Riverside, RI
Safran	Paris, France
Saint Gobain	Courbevoie, France
Sandvik	Stockholm, France

Company	Headquarters
Showa Denko	Tokyo Japan
Sumitomo Electric Industries	Osaka, Japan
Tomei Diamond	Tokyo, Japan
Tungaloy	Iwaki-city, Japan
Ultramet	Pacoima, CA
Wuxi Sundi Precision Tools	Wuxi, China
Xiamen Innovacera Advanced Materials	Xiamen, China
Xiamen Unipretec Ceramic Technology	Xiamen, China
Zhengzhou Berlt Hard Material	Zhengzhou, China
Zibo Deming Advanced Materials	Shandong, China
Zibo Jonye Ceramic Technologies	Shandong, China
Zibo Sinyo Nitride Materials	Zibo City, China

Source: BCC Research

There are 8 producers of MAX phase ceramics, 75% of which are headquartered in Europe and the remaining 25% in the U.S.

Table 55
Leading Manufacturers of MAX Phase Ceramics, 2020

Company	Headquarters
Ansaldo Energia	Genoa, Italy
Haldor Topsoe	Lyngby, Denmark
NASA Glenn Research Center	Cleveland, OH
Raytheon Technologies	Waltham, MA
Rolls-Royce	London, U.K.
Safran	Paris, France
Sandvik	Stockholm, France
Siemens	Munich, Germany

Source: BCC Research

To summarize, 48.8% of the total number of firms supply UHTC monoliths and coatings; 41.5% produce UHTC composites; and the remaining 9.8% supply MAX phase ceramics. No producer of high-entropy ceramics was found, being these products still in the development stage. The total count is 82, rather than 60, because several firms are suppliers of more than one type of advance material product.

Most U.S. firms (61.8%) produce UHTC monoliths and coatings, while UHTC composites are fabricated by 32.4% of U.S. companies, and MAX phase ceramics are made by 5.9% of U.S. firms.

European manufacturers specialize primarily in UHTC composites (36.8% of total European firms), followed by UHTC monoliths and MAX phase ceramics with equal share of 31.6%.

In the Asia-Pacific region, 53.6% of all firms currently produce UHTC composites, whereas 46.4% manufacture UHTC monoliths and coatings.

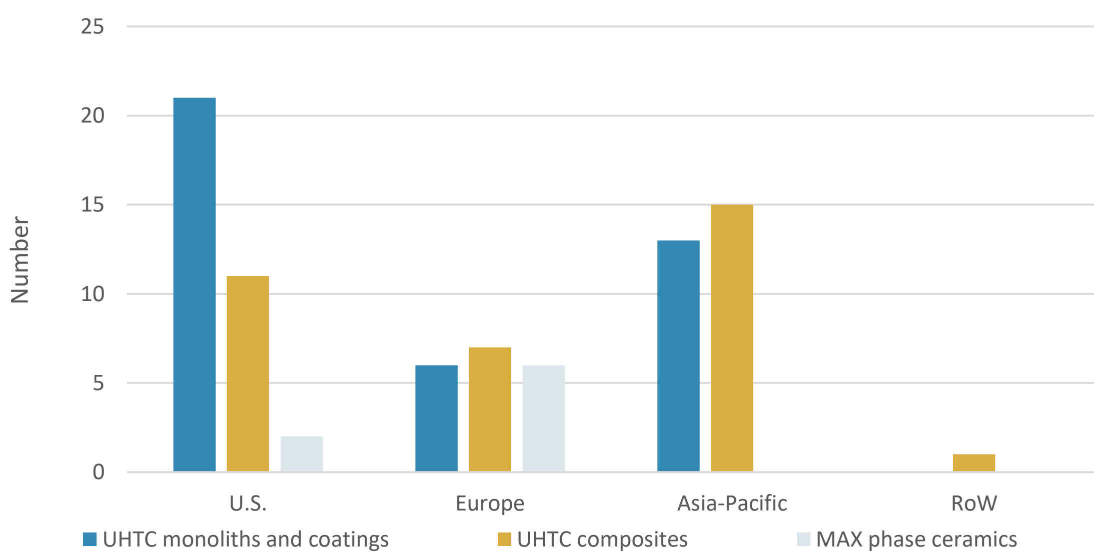
The only organization found in the Rest of the World is a manufacturer of UHTC composites.

Table 56
Leading Manufacturers of Advanced Materials and Products for Extreme Environments, by Type of Material and Region, 2020
(Number)

Type of Material	U.S.	Europe	Asia-Pacific	RoW	Total
UHTC monoliths and coatings	21	6	13	0	40
UHTC composites	11	7	15	1	34
MAX phase ceramics	2	6	0	0	8
Total	34	19	28	1	82

Source: BCC Research

Figure 42
Distribution of Manufacturers of Advanced Materials and Products for Extreme Environments, by Type of Material and Region, 2020
(Number)



Source: BCC Research

Other Industry Players

The following table lists other relevant industry players, including suppliers of raw materials, producers of fabrication equipment, suppliers of advanced ceramic matrix composites, and future market participants. Although not a comprehensive list, it does include those companies that are contributing to the growth of the market for advanced materials for extreme environments.

Table 57
Other Relevant Industry Players in the Market for Advanced Materials and Products for Extreme Environments, 2020

Company	Headquarters	Relevant Products/Services
Aerojet Rocketdyne	Sacramento, CA	CMCs and 3D manufacturing
ALB Materials	Henderson, NV	Supplier of materials for fabrication of advanced materials and products for extreme environments
Albany Engineered Composites	Rochester, NH	CMCs for engine hot zones, thermal shields, and high-temperature products
AltaSim Technologies	Columbus, OH	Analysis and modeling of CMCs
American Elements	Los Angeles	Supplier of materials for fabrication of advanced materials and products for extreme environments
Beckwood Press	Fenton, MO	Hydraulic presses for CMC fabrication
Bettini	Monte Marenzo, Italy	CMCs for the aerospace industry
Carbon Ukraine	Kiev, Ukraine	Supplier of materials for fabrication of advanced materials and products for extreme environments
CeramTec	Plochingen, Germany	CMC cutting tools and inserts
Composite Horizons	Covina, CA	CMCs for high temperature applications
Covaron Advanced Materials	Ann Arbor, MI	CMCs from polymeric precursors
Dandong Chemical Engineering Institute	Langtou Town	Supplier of materials for fabrication of advanced materials and products for extreme environments
Dr. Fritsch	Fellback, Germany	Producer of spark plasma sintering furnaces
Easy Fashion Industry	Changsha, China	Producer of spark plasma sintering furnaces
Edgetech Industries	Miramar, FL	Supplier of materials for fabrication of advanced materials and products for extreme environments
Element Cincinnati	Fairfield, OH	Testing of ceramic matrix composites
Eno Material	Qinhuangdao City, China	Supplier of materials for fabrication of advanced materials and products for extreme environments
FCT Systeme	Frankenblick, Germany	Producer of spark plasma sintering furnaces
FMI	Biddeford, ME	CMCs for aerospace and defense, and high temperature applications
Free Form Fibers	Saratoga Springs, NY	Inorganic fibers for CMCs
Fuji Electronic Industrial	Saitama, Japan	Producer of spark plasma sintering systems
H.C. Starck	Munich, Germany	Supplier of materials for fabrication of advanced materials and products for extreme environments
Harper International	Buffalo, NY	Kilns for sintering of CMCs

Company	Headquarters	Relevant Products/Services
Hongwu International Group	Guangzhou, China	Supplier of materials for fabrication of advanced materials and products for extreme environments
Hunan Huawei Jingcheng Material Technology	Hunan, China	Supplier of materials for fabrication of advanced materials and products for extreme environments
IHI	Tokyo, Japan	CMCs for turbine vanes and other turbine components
Japan New Metals	Osaka, Japan	Supplier of materials for fabrication of advanced materials and products for extreme environments
Kawasaki Heavy Industries	Tokyo, Japan	CMCs for gas turbines
Kyocera	Kyoto, Japan	CMCs for various applications
Materials Research & Design	Wayne, PA	CMCs for the aerospace industry
Mitsubishi Heavy Industries	Tokyo, Japan	CMCs for gas turbines
MT Aerospace	Augsburg, Germany	CMCs for space applications
MTI	Richmond, CA	Producer of spark plasma sintering equipment
NGK Spark Plug	Tokyo, Japan	CMC cutting tools
NGS Advanced Fibers	Toyama, Japan	Producer of SiC fibers for CMCs
NJS	Kanagawa, Japan	Producer of spark plasma sintering equipment
Plasan North America	Walker, MI	CMCs for armor products
Pred Materials International	New York, NY	Supplier of materials for fabrication of advanced materials and products for extreme environments
Simuwu	Shanghai, China	Producer of spark plasma sintering furnaces
Sinter Land	Nagaoka City, Japan	Producer of spark plasma sintering furnaces
Specialty Materials	Lowell, MA	Boron and SiC fibers for CMCs
Starfire Systems	Schenectady, NY	Ceramic precursors for SiC matrix composites
Sumitomo Electric Industries	Osaka, Japan	CMCs for thermal management
T.E.A.M.	Woonsocket, RI	Wowen fabrics for use as reinforcement in CAMCs and CMCs
TaeguTec Cutting Tools	Daegu, South Korea	Alumina matrix composites for cutting tools and wear-resistant parts
Technology Assessment and Transfer	Annapolis, MD	Ceramic matrix composites; 3D manufacturing
Teledyne Scientific	Thousand Oaks, CA	CMCs for aerospace applications
Thermal Technology	Santa Rosa, CA	Producer of spark plasma sintering systems and hot-pressing systems
Treibacher Industrie	Althofen, Austria	Supplier of materials for fabrication of advanced materials and products for extreme environments
Unifrax	Tonawanda, NY	Ceramic fibers for composites
US Research Nanomaterials	Houston, TX	Supplier of materials for fabrication of advanced materials and products for extreme environments

Source: BCC Research

Company Profiles

The following are current profiles of 20 leading manufacturers of advanced materials and products for extreme environments, listed in alphabetical order. The objective is to offer a more detailed picture of the key players involved in the fabrication and commercialization of advanced materials for extreme environments. These companies are intended to be a representative sample of the entire industry.

3M

3M Center
St. Paul, MN 55144
Tel: 651/733-1110
Website: www.3M.com

Formerly known as Minnesota Mining and Manufacturing Company, 3M started its operations in 1902 and was incorporated in 1929. 3M manufactures a variety of products serving markets such as electronics, automotive, construction, renewable energy, paper and packaging, food and beverage, and appliances. The company's business is composed of four segments:

- Safety and industrial, which serves the industrial, electrical and safety sectors, offering supplies for the safety, security, and productivity of workers, facilities, and systems, as well as products for commercial graphics, the automotive aftermarket, roofing, and personal hygiene, among others.

- Health care, which serves markets such as medical clinics and hospitals, pharmaceuticals, dental and orthodontic practitioners, and health information systems.

- Transportation and electronics, which serves the transportation and electronic original equipment manufacturer (OEM) markets.

- Consumer, which sells office supplies and stationery, as well as construction and home improvement, home care, and consumer health care products.

Within the transportation and electronics segment operates the advanced materials division, which also produces advanced technical ceramics for application in the automotive, oil and gas, solar, industrial, electronics, and defense sectors, including ceramic matrix composites.

3M offers alumino-silicate fibers for CMCs under the Nextel trade name. Nextel fibers are produced as fabrics, tapes, sleevings, chopped fibers, and yarns that can be easily converted into textiles, for use in high-temperature operating environments. Nextel fibers can be used for both continuously and discontinuously reinforced ceramic matrix composites.

In 2012, 3M purchased Ceradyne, a leading developer and producer of advanced technical ceramics, located in Costa Mesa, CA. Ceradyne has been integrated within the Advanced Materials division.

Through the acquisition of Ceradyne, 3M has added the following UHTCs to its product portfolio:

- TiB_2, ZrB_2 and BN powders and components. Products are available in many forms, such as bearings, seal rings, blast nozzles, and crucibles.

- Boron nitride composites, under the tradenames Sintered Boron Nitride (previously Mycrosint) SO_{20} and SO_{43} (composites based on BN, ZrO_2 and SiC) and O_{40} (BN, ZrO_2, and B_2O_3). These materials are used to manufacture crucibles as well as nozzles and break rings for continuous casting of metals. 3M boron nitride composites are claimed to increase the lifetime of steel, copper alloys, nickel alloys, superalloys, and precious metals.

- Evaporation boats made from two (Dimet) or three (Trimet) components: titanium diboride, boron nitride (Dimet) and aluminum nitride (Trimet). These evaporation boats provide high evaporation rates in combination with long life-time and high corrosion resistance

3M reported total sales of $32.1 billion in 2019, of which $1.3 billion were generated by the advanced materials division. The U.S. accounted for 41.2% of global sales, followed by Asia-Pacific (19.5%), Europe (22.3%), and the Rest of the World (17.0%).

ABLE TARGET

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China
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Website: www.abletarget.com

Established in 2001, Able Target specializes in the development, production and sales of thin film coating materials. The company has several production lines built to satisfy multiple applications and to manufacture materials with optimized properties.

Able Target sells sputtering targets and evaporation materials for fabrication of flat panel displays, solar cells, semiconductor devices, data storage devices, glass coatings, decorative coatings, and wear resistant coatings. These products are fabricated by powder metallurgy, casting and smelting.

Sputtering targets come in three standard shapes (rectangular, round, and rotatable) and with purities ranging from 99.5% to 99.9999%. Custom made targets can be manufactured upon request.

Also, various materials are available in the form or pure metals (e.g., gold, chromium, nickel, tungsten, and molybdenum), alloys (e.g., aluminum chromium, gold alloys, nickel alloys, titanium aluminum, and nickel chromium) and ceramics.

Ceramic targets include oxides (e.g., silica, alumina, titania, indium tin oxide, and aluminum zinc oxide) and non-oxides (e.g., carbides, nitrides, sulfides, selenides, and tellurides). In particular, Able Target offers UHTC targets consisting of the following:

- Zirconium diboride (ZrB_2), hafnium diboride (HfB_2), tantalum diboride (TaB_2), and titanium diboride (TiB_2).
- Hafnium carbide (HfC), tantalum carbide (TaC), titanium carbide (TiC), niobium carbide (NbC), and zirconium carbide (ZrC).
- Hafnium nitride (HfN), tantalum nitride (TaN), and boron nitride (BN).

These UHTCs have purities ranging from 99.5% to 99.999% and are available in the three standard shapes as well as in custom-made shapes. They are also sold in the form of granules, pellets, crucibles, and boats for use in evaporation systems.

ARIANEGROUP

66 Route de Verneuil
78130 Les Mureaux
France
Tel: +33-160-87-60-00
Website: www.ariane.group

ArianeGroup is a leading European organization operating in the aerospace, defense and security fields. The company was established in 2015 as a joint venture between Airbus (Leiden, the Netherlands) and Safran (Paris, France—see below). Originally named Airbus Safran Launchers, it became ArianeGroup in 2017.

The company is involved in all aspects of rocket launching, including launcher design, development, production, operation, and commercial services. With approximately 9,000 employees, ArianeGroup has 12 facilities located in France, France Guiana, and Germany.

As part of various space programs, ArianeGroup is participating in the design, development and production of ultrahigh temperature ceramic matrix composites for re-entry and hypersonic vehicles. These UHTC composites are being applied in the fabrication of near-zero erosion nozzles for high-performance rockets and near-zero ablation thermal protection system (TPS) tiles that can withstand high heat fluxes during lunch and re-entry.

ArianeGroup had estimated 2019 revenues of approximately $4.1 billion.

ATLANTIC EQUIPMENT ENGINEERS

24 Industrial Ave.
P.O. Box 181
Upper Saddle River, NJ 07458
Tel: 800/486-2436
Website: www.micronmetals.com

Founded in 1963, Atlantic Equipment Engineers manufactures and sells products based on high-purity metals and non-metals, alloys, and ceramics.

The company primarily fabricates sputtering targets with purities up to 99.999% made from elements (e.g., antimony, bismuth, boron, copper, and chromium), oxides (e.g., aluminum oxide, bismuth trioxide, cobalt oxide, and germanium dioxide), and non-oxides (e.g., aluminum nitride, boron carbide, and chromium disilicide). Atlantic Equipment Engineers' offering also includes powders, rods, ingots, shots, coatings, and fabricated forms.

Products for ultrahigh temperature applications include:

- Hafnium carbide sputtering targets, with purities ranging between 99.5% and 99.95%.
- Boron nitride sputtering targets, with purity of 99.5%.
- Boron nitride crucible liners.
- Boron nitride rods with 99.9% purity.
- Tantalum carbide rods.

In addition, Atlantic Equipment Engineers sells a range of high-purity diboride, carbide and nitride powders for fabrication of advanced ceramic materials for extreme environments:

- Hafnium diboride (99.8% purity), zirconium diboride (99.9%), titanium diboride (99.7%), and niobium diboride (99.8%).
- Hafnium carbide (99.9%), tantalum carbide (99.8%), zirconium carbide (99.8%), niobium carbide (99.8%), and titanium carbide (99.9%).
- Tantalum nitride (99.8%) and boron nitride (99.9%).

COORSTEK

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

CoorsTek originated in 1910 when Adolph Coors (the founder of the Adolph Coors brewery) invested in Herold China and Pottery Co., a manufacturer of oven-safe porcelain. The company was renamed Coors Porcelain in 1920 and Coors Ceramics in 1986. In 1992 Adolph Coors Co. spun-off ACX Technologies, which included Coors Ceramics and other non-brewery assets. On Jan. 1, 2000 CoorsTek was in turn spun-off from ACX Technologies and began its existence as a separate company.

Today, CoorsTek represents the largest technical ceramics manufacturer in North America and has manufacturing facilities in Europe and Asia. CoorsTek produces ceramic products to serve a number of industries: aerospace and aviation components, ceramic armor, ceramic air-bearing guideways, electronic ceramics, ceramics for food and beverage, components for lasers, parts for industrial applications, medical device components, parts for fuel cells, sensors and membranes, and many others.

In September 2011, CoorsTek purchased BAE Systems' Advanced Ceramics business in Vista, CA. BAE Systems (London, U.K.) was established in 1999 from the merging of British Aerospace with GEC Marconi Electronic Systems, and is one of the world largest suppliers to the defense and national security sector. The company sells vehicles (e.g., military aircrafts and armored tanks) as well as systems and components (e.g., missiles, air defense systems, and equipment for cyber security and intelligence).

BAE Systems' Advanced Ceramics Division was previously named Cercom Inc. and was a subsidiary of United Defense Industries (UDI). UDI was acquired by BAE Systems in June 2005. Cercom was founded in 1985 and was dedicated to the development and fabrication of advanced ceramics and CMCs.

Products of BAE's Advanced Ceramic Division included body armor (including armors made from UHTCs), ceramic balls, bearings, insert blanks, seals, semiconductors, housings, microwave components, nozzles, wear-resistant parts, crucibles, and grinding media. These products are made for use in stringent applications within the aerospace, petroleum, automotive, defense, electronics, and industrial sectors.

With this important acquisition, CoorsTek further expanded its offering of technical ceramic, CMC products, and ceramics for extreme environments. Among its specialty engineered ceramics division, the company manufactures components made from titanium diboride. This material, which is characterized by flexural strength of 275 MPa, fracture toughness of 6.9 MPa · $m^{1/2}$, and coefficient of thermal expansion of 8x10-6/°C, is particularly well suited for ballistic protection.

CoorsTek had estimated revenues of approximately $850 million in 2019.

GE AVIATION

1 Neumann Way
Cincinnati, OH 45215
Tel: 513/552 3272
Website: www.geaviation.com

GE Aviation is a division of General Electric. General Electric has its origins in 1878, when Thomas Edison, the inventor of the first commercially practical incandescent lamp, formed the Edison Electric Light Company. In 1892, General Electric (GE) was formed from the merging of Edison General Electric Company and the Thomas-Houston Company.

Although GE's initial business was the manufacturing of machinery and components for production and distribution of electricity, during the 142 years since its foundation, the company has grown to become one of the largest corporations worldwide. Today GE, which had global revenues of $95.2 billion in 2019, comprises two main businesses: industrial and financial solutions.

GE industrial includes the following segments: power, renewable energy, aviation, and healthcare. In 2019, GE Aviation accounted for 34.5% of global sales.

GE Aviation Ceramic Composite Products and Its History

Within GE Aviation operates GE Aviation Ceramic Composite Products, a subsidiary that has its origins in Lanxide Armor Products (LAP). LAP was founded in 1988 with headquarters in Newark, DE. The company specialized in the fabrication of high-performance CMC armor. In the following years, LAP created joint ventures with Alcan Aluminum Corp. (Alanx Wear Solutions, Newark, DE) and DuPont (DuPont Lanxide, Newark, DE) to develop and manufacture ceramic composites for various other applications (gas filters, thermostructural components, combustor liners, radiant tubes, and wear-resistant materials). In 1998, the three companies were acquired by Allied Signal, thus becoming Allied Signal Composites. In 1999, Allied Signal merged with Honeywell and the new group adopted the Honeywell name. Allied Signal Composites became Honeywell Advanced Composites. In 2000, due to air pollution violations, the Newark-Marrows Road facility (formerly Lanxide Armor Products) was closed and its operations merged with operations at the Belleview Road facility (ex-DuPont Lanxide).

Honeywell Advanced Composites was sold to General Electric in 2001 after plans for a merger between GE and Honeywell were called off. The company was renamed GE Ceramic Composite Products. The third Newark facility on Lake Drive (formerly Alanx Wear Solutions) was acquired in 2004 by a company specializing in armor products and eventually closed.

Current Activities

Presently, GE Aviation Ceramic Composite Products provides a wide range of advanced CMC components for aircraft and land-based turbine engines, rocket motors, aerospace hot structures, and industrial applications. The company specializes in material development, design consultation, CMC fabrication, machining, mechanical properties testing, and non-destructive inspection.

Products are fabricated by melt infiltration (MI) or chemical vapor infiltration (CVI) and consist primarily of SiC matrix composites for components (vanes, blades, shrouds, and liners) used in turbine engine hot sections, as well as light-weight mirrors, optical benches and structures, heat exchangers, and high-temperature corrosion structures.

GE, however, manufactures also other CMC types. The company has been developing and utilizing high-density zirconium, titanium, and tantalum borides since the 1960s. Utilizing this know-how, GE is able to produce CMCs that can withstand temperatures up to 2500°C.

In particular, GE has developed a titanium diboride with density up to 96.6% of theoretical, Vicker hardness of 2,520 kg/mm^2 and flexure strength of 569 MPa using a self-propagating rapid reaction of titanium and boron. This material is being applied in the fabrication of components for re-entry systems and nuclear reactors.

In addition, GE has introduced TiB_2 matrix composites for roller bearings and other wear and corrosion-resistant components, characterized by very high hardness and toughness, which can operate under very high stress conditions as those found in aerospace applications. Other products based on TiB_2 matrix composites are evaporation boats for high temperature vacuum metallization.

KENNAMETAL

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Kennametal was established in 1938 when, after years of research, metallurgist Philip M. McKenna created a tungsten-titanium carbide alloy for cutting tools that provided a productivity breakthrough in the machining of steel. Kennametal's tools cut faster and lasted longer, and thereby facilitated metalworking in products from automobiles to airliners to machinery.

Today, in addition to its primary business of manufacturing metal working tools, the company produces tools for energy, mining, and construction; advanced materials with wear-resistant properties; deburring and surface finishing solutions; carbide and superalloy cutting tools; and carbide, metal alloy, and thermal spray powders.

Kennametal has long-standing expertise in the preparation and processing of titanium diboride and boron nitride powders. In addition to sell these materials, the company uses them to manufacture several types of AMEE monolithic and composite products:

- Evaporation boats, made from a composite comprising boron nitride and titanium diboride.

- Hot isostatically pressed boron nitride, sold under the trade name Hatemit. This ceramic, which exhibits high thermal shock resistance, low thermal expansion, and high chemical resistance, is suitable for molten metal channel and pump components, crucibles, horizontal casting break rings, high-power transistor insulators, nozzles for non-ferrous metals, evaporation boats, and linings for plasma chambers.

- Hot pressed boron nitride with aluminum nitride, zirconia, or silica for casting nozzles, atomizing nozzles, parts for nuclear plants, high-temperature bearings, and high-temperature/high-moisture components.

- TiB_2 matrix composite cutting tools for high-speed machining of group IV metal and alloys, especially titanium and its alloys.

Kennametal reported worldwide sales of $2.4 billion in 2019. The U.S. represented the largest market, accounting for 42.7% of Kennametal's global sales, followed by Europe (25.3%) the Asia-Pacific region (22.7%), and the Rest of the World (9.3%).

MATECH

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Since its founding in 1989, Matech has specialized in the fabrication of various materials by chemical polymerization methods, including optical and electronic materials, biomaterials, and high-temperature ceramics and composites.

Through funding received by different organizations, including the National Science Foundation, the Missile Defense Agency and the U.S. Department of Energy, Matech has developed several types of ceramic matrix composites based on preceramic polymers.

Matech utilizes a fully integrated process to produce its CMCs. The process consists of ceramic fibers manufacturing, fabric weaving, interface coating, impregnation, and sintering, adopting techniques such as PIP, CVI, hybrid CVI/PIP, and spark plasma sintering.

The company fabricates an ultrahigh temperature CMC based on a zirconium oxycarbide matrix reinforced with carbon fibers. The product is available in various shapes and sizes and is used for missile propulsion components and thermal protection systems.

MATERION

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Established in 1931, Materion Corp. was previously known as Brush Engineered Materials. The company changed its name in 2011 to reflect its focus on advanced materials, while, at the same time, it unified all of its businesses under the new Materion brand.

Materion produces inorganic chemicals, optical and thin film coatings, engineered ceramics, thin film deposition materials, beryllium, beryllium-based metal matrix composites, high-performance alloys, and other technical materials.

Currently the company comprises four business segments: performance alloys and composites, advanced materials, precision coatings, and other.

The advanced materials segment focuses on advanced chemicals, microelectronics packaging, precious and non-precious packaging, and specialty metal products, which include thin film deposition materials (i.e., sputtering targets and evaporation materials).

The division produces rectangular, rotatable and large area targets, and targets with custom shapes and sizes. Large area targets, which are available in rectangular and cylindrical configurations, can be manufactured up to 4 meters in length and are available with monolithic design, or using inlay construction by close-fitting two or more sections with overlapping joints.

Sputtering targets are fabricated in a variety of compositions (base and precious metals, alloys, cermets, borides, carbides, nitrides, fluorides, silicides, oxides, chalcogenides, selenides, and others) and different purity levels. Target purities range from 99.0% to 99.9999% depending on the material and application. Many of the materials used are synthesized in-house.

To manufacture its metal targets, Materion utilizes various processes based on the following capabilities: casting, vibration casting (VCT), ceramic sintering, cold and hot isostatic pressing, extrusion, hot and cold rolling, inert gas hot pressing, plasma spray, precision machining, vacuum hot pressing, and vacuum arc or induction melting.

Materion is a fully integrated manufacturer with in-house refining and recycling services as well as extensive analytical capabilities. Besides metal refining and recycling, Materion offers backing plates, bonding services, and shield stripping/repair.

Apart from sputtering targets, Materion sells evaporation materials in the form of coarse and fine powders, granules, pellets, slugs, rods, and wires. Standard materials comprise precious and non-precious metals, alloys, metal halides, oxides, and nitrides, with purity levels up to 5N.

In addition to standard compositions, Materion is capable of preparing raw materials to meet customer specifications in terms of form, size, purity or compounds. In particular, the company offers complex composites produced by hot pressing and special alloys manufactured by vacuum casting.

Among many other material compositions, Materion offers the complete range of UHTC formulations in the form of powders, granules, pellets, wires, slugs, and targets and most of them with 99.5% purity:

- Hafnium, zirconium, tantalum, titanium, and niobium diborides.
- Hafnium, zirconium, titanium, tantalum, and niobium carbides.
- Hafnium, tantalum, and boron nitride.

Thin film deposition materials are used in the fabrication of optical and magnetic data storage media, microelectronics, optoelectronics, flat panel displays, photovoltaic cells, wear resistant coatings, optical coatings, and medical coatings.

Materion had estimated global revenues of $1.2 billion in 2019. The U.S. represented the largest market, accounting for 62.7% of total sales, followed by the Asia-Pacific region (21.6%), Europe (14.3%) and the Rest of the World (1.4%).

MORGAN ADVANCED MATERIALS

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Morgan Advanced Materials was founded in 1856 as a factory of crucibles located in the London suburb of Battersea. Over the years, the Morgan Crucible Company expanded and added other products including commutator brushes, steatite and porcelain components, ceramic-to-metal assemblies, high-temperature parts, seal and bearings, ceramic cores for investment casting, piezoelectric actuators, and high-tech composites for armor systems, which are fabricated in 80 manufacturing facilities worldwide. As a result, in 2013 the company changed its name to Morgan Advanced Materials.

Morgan Advanced Materials produces both oxide and non-oxide ceramics. Morgan's technical ceramics are used in applications that demand exceptional wear and corrosion resistance, high mechanical strength, high fracture toughness, and high-temperature resistance. These applications include pump components, valves, inserts for cutting tools, and advanced components for nuclear plants, defense, and high-temperature applications.

The company offers a high-purity (99.995%) pyrolytic (hexagonal) boron nitride ceramic grown by chemical vapor deposition (CVD) and characterized by anisotropic properties because of its planar crystal structure. The main properties of this ceramic are very high temperature stability and oxidation resistance, high thermal shock resistance, good flexural strength, and superior chemical inertness to acid, bases, organic solvents, and molten metals.

Morgan Advanced Materials reported global revenues of $1.3 billion in 2019. The U.S. accounted for 40.0% of total sales, followed by the Asian region (28.3%), Europe (25.9%), with the remaining 5.8% occurring in the rest of the world.

PLANSEE

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Plansee was established in 1921 by Prof. Paul Schwarzkopf as a producer of molybdenum and tungsten wires. The company still specializes in the processing of refractory metals by powder metallurgy. In addition to molybdenum and tungsten, Plansee sells products made from tantalum, titanium, niobium, chromium and their alloys.

These products consist of thin film materials, semifinished materials, and several types of components for furnace construction, lamps, electronic thermal management, mechanical tools, coating systems, and radiation generation and protection equipment.

For ultrahigh temperature applications, Plansee offers high-density titanium diboride sputtering targets characterized by very fine microstructure, high resistance to thermal shocks, purity as high as 99.7%, and thermal conductivity of 64 W/(mK). These targets are produced by hot pressing at temperatures ranging between 1700°C and 2000°C, and due to their manufacturing process, no particles are ejected during sputtering, allowing to achieve very smooth coatings.

RAYTHEON TECHNOLOGIES

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RaytheonTechnologies (RTX) was recently formed by the merger of Raytheon (Waltham, MA) and United Technologies (Farmington, CT). This consolidation, which was completed in April 2020, created an organization with estimated $90 billion in 2019 that focuses on advanced technologies for the aerospace and defense industries.

The new company comprises four business segments: Collins Aerospace, Pratt & Whitney, Raytheon Intelligence & Space, and Raytheon Missiles & Defense.

Advanced materials for extreme environments are developed and produced by Pratt & Whitney, which supplies aircraft engines, and Collins Aerospace, which provides advanced aerospace solutions, interior systems and information management technologies for commercial, business, and military aircrafts.

Within these two divisions, RTX fabricates primarily C/SiC and SiC/SiC ceramic composites used for fabrication of hot sections of gas turbine engines (e.g., combustors). To protect gas turbine components from extreme temperatures, the company has introduced thermal and environmental barrier coatings based on metal diborides and MAX phase ceramics.

Metal diborides are used to create wear-resistant coatings for turbine blades that maximize engine efficiency.

MAX phase ceramics contain aluminum, which promotes the formation of thermally grown oxides with rapid self-healing properties at temperatures higher than 1090°C. Examples of these materials are Cr_2AlC, Ti_2AlC, and Ti_2AlN.

READE

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Reade International (also known simply as Reade) was originally founded in 1773, in England, as a producer of pharmaceutical chemicals. About 100 years later the company was relocated to the U.S. and continued to expand as a supplier of specialty chemicals. Currently, Reade sells a wide range of metals, metal alloys, ceramics, composites, abrasives, nanomaterials, and other high-tech chemicals.

Reade offers the following advanced materials and products for extreme environments:

- Hafnium, niobium, tantalum, titanium, and zirconium diborides with minimum purity of 99%, in the form of powders, granules, ingots, and sputtering targets.

- Hafnium nitride with purities ranging from 99% to 99.5%, in the form of powder, sintered compacts, and sputtering targets.

- Tantalum nitride with purity of 99.5% in the form powder, granules, sintered compacts, and sputtering targets.

- Boron nitride, with at least 86% purity, in the form of powder, granules, sintered pieces, rods, and sputtering targets.

SAFRAN

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Safran was created in 2005 by the merging of two other French companies, Snecma (a large producer of aircraft engines and other components) and Sagem (a company involved in defense and consumer electronics, and communication systems).

With global revenues estimated at $23 billion in 2019, Safran is a leading producer of helicopter, aircraft and rocket engines; electronics and electrical systems for aerospace and defense; aircraft landing and braking systems; identity and security solutions; power transmission systems; and advanced ceramic materials.

Safran Ceramics is dedicated to the development and manufacturing of ceramic matrix composites for high temperature applications, specifically for use in aircraft hot sections, such as turbines and nozzles. Safran's CMC technology is based primarily on SiC matrix composites originally developed by Snecma Propulsion Laboratory.

However, Safran Ceramics is also producing several types of AMEE materials:

- Boride matrix composites reinforced with whiskers characterized by reduced shrinkage and better reliability, for turbojet engines

- Dysprosium boride/hafnium carbide coatings with atomic ratio Hf/Dy equal to 2.7 for withstanding temperatures greater than 2050°C under oxidizing atmosphere

- Titanium diboride composites for protective coating of oxidation-sensitive components

- Tantalum boride/hafnium carbide/hafnium boride ceramics produced by spark plasma sintering for corrosive atmosphere at temperatures higher than 2200°C

- MAX phase matrix composites with self-healing properties based on Ti_3SiC_2.

SAINT-GOBAIN

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Created in 1665 to help restore the French economy, Saint-Gobain has remained through the centuries one of the leading producers of glass and glass products.

Today, Saint-Gobain sells glass for interior and exterior finishing, coated glass, energy efficient solutions, high-performance materials, heavy building materials, sanitaryware, timber and panels, roofing, and ceramic tiles.

Within the high-performance materials division, Saint-Gobain offers ceramic products, such as silicon carbide, zirconium-based abrasive grains, ceramic balls, and refractories for the glass industry.

Saint-Gobain Ceramic Materials also manufactures the following boron nitride-based ceramics and composites under the Combat brand name:

- Combat Grade AX05, a machinable hexagonal boron nitride with purity of 99.7%. It exhibits high temperature resistance at 2000°C in both inert and vacuum conditions.

- Combat Grade A, a hot-pressed hexagonal boron nitride that contains a boron oxide binder for improved mechanical strength.

- Combat Grade HP, which utilizes a calcium borate binder and is characterized by low thermal expansion in addition to high thermal resistance.

- Combat Grade M and M26, two composite materials with silica as the second phase, suitable for applications up to 1400°C.

- Combat Grade ZSBN, which combines the thermal properties of hot-pressed boron nitride with the mechanical strength and inertness of silicon carbide and zirconia. It is suitable for the production of wear, corrosion and high-temperature resistant components such as crucibles, molds, valves, break rings, nozzles, bearings and high-temperature fixtures.

- Combat Grade SiZBN, a new hot-pressed composite obtained by combining boron nitride with zirconia and SiAlON. This material is suitable for processing of molten metals and steel.

Saint-Gobain had global sales of $47.6 billion in 2019. Europe accounted for 79.32% of global sales, followed by the Americas (15.5%), and Asia-Pacific (5.2%).

SANDVIK

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Founded in 1863, Sandvik is a high-technology and engineering group that operates in three main areas: machining (i.e., tools and tooling systems for metal cutting); mining and rock technology (i.e., equipment and tools for the mining and construction industries); and materials (i.e., products made with advanced stainless steels and special alloys).

The machining solutions division sells cutting tools and tooling systems under brands such as Sandvik Coromant, Seco, Walter, Wolfram, and Dormer Pramet.

Sandvik Coromant supplies a wide range of products, including fully-finished tools such as carbide rotary cutters for the nonwovens industry, can tooling for the can industry, and rolls for the steel industry.

The company offers polycrystalline cubic boron nitride cutting tools, characterized by elevated hardness, fracture toughness and thermal shock resistance, suitable for finish turning of hardened steels at very high cutting speeds.

The company also produces alumina/TiC (CC650 and the TiN coated CC6050) for high-speed finishing of cast iron, hardened steel, and heat resistant superalloys where the combination of wear resistance and good thermal properties is required.

In addition, Sandvik has introduced holding fixtures for inserts, such as pyramid cones, fabricated from a MAX phase ceramic based on Ti_3SiC_2. This material is characterized by outstanding properties including high thermal shock resistance, damage tolerance, fracture toughness, temperature resistance, oxidation and corrosion resistance, and machinability.

Sandvik reported global sales of $12.1 billion in 2019. Sandvik Machining Solutions accounted for 40% of the total. Europe represented 37% of global revenues, followed North America (23%), the Rest of the World (21%), and Asia (19%).

SHANGHAI KESSEN CERAMICS

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Shanghai Kessen Ceramics (SKC) is involved in the development, manufacturing and commercialization of technical ceramics including refractory materials, oxides, and non-oxides.

The company specializes in the fabrication of materials that exhibit resistance to high temperatures, and exceptional wear and corrosion conditions. These materials find application in many sectors, such as metallurgy, petrochemical, aerospace, defense, energy, automotive, and electronics.

SKC offers the following advanced materials and products for extreme environments:

- Zirconium diboride ceramics, with purity of 99.5%, bending strength of 1,555 GPa, and maximum operating temperature of 3040°C under vacuum.

- Titanium diboride ceramics, with purity greater than 99.9% and maximum operating temperature of 2980°C.

- Boron nitride ceramics, with purity of 99%, compressive strength of 200 MPa, good thermal shock resistance, and maximum operating temperature of 3000°C.

- Boron nitride crucibles, with purity greater than 99%, compressive strength of 350 MPa, bending strength of 100 MPa, and maximum operating temperature of 2400°C.

These products are manufactured in a fully-integrated plant capable of synthesizing high-purity powders and carrying out the sintering process at very high temperatures and under pressure. In addition, SKC is equipped with a state-of-the-art R&D facility for development of new materials and participates in research projects with the Chinese Academy of Science, the Massachusetts Institute of Technology and other relevant research organizations.

SIEMENS

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Siemens was founded in 1847 and was initially a provider of long-distance telegraph lines. Eventually its business expanded to other telecommunication and electrical systems, penetrating also the energy supply sector. Today, Siemens is one of the largest manufacturing companies in Europe and offers a wide range of products and services related to gas and power supply, smart infrastructure, renewable energy, industrial automation, water treatment, urban and freight transportation, and healthcare.

For the energy sector Siemens manufactures many types of gas turbines that fulfill different requirements in terms of efficiency, reliability, and flexibility. These turbines are designed for heavy-duty, industrial, and lightweight applications.

For the fabrication of some gas turbine components (e.g., ring seals and blade tips), Siemens has recently introduced MAX phase materials such as Ti_3SiC_2 and Cr_2AlC. These ceramics are produced by conventional routes (e.g., hot isostatic pressing starting from powders) or by selective laser melting to achieve near-net shape manufacturing.

Siemens reported global revenues of $97.3 billion in 2019.

T.Q. ABRASIVE MACHINING

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Established in 1994, T.Q. Abrasive Machining is involved in the fabrication and close-tolerance machining of technical ceramics for aerospace, defense, automotive, nuclear, medical, and electronics applications.

The company produces ceramic rods, tubes, tiles, sputtering targets, ball bearings, and other shapes made from various materials, including titanium diboride, titanium carbide, and boron nitride.

Parts are fabricated according to the customer's specifications.

ULTRAMET

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Ultramet was created in 1970 as a supplier of high-temperature materials for chemical and nuclear applications. Currently, the company offers chemical vapor deposition services and also produces components for satellite propulsion systems and medical implants.

Ultramet manufactures continuously reinforced ceramic matrix composites by rapid melt infiltration. These CMCs are characterized by high density (greater than 98% of theoretical), reduced microcracking, low-cost raw materials and processing, and relatively short fabrication time.

The company produces carbon fiber-reinforced CMCs with zirconium carbide, hafnium carbide, tantalum carbide, niobium carbide and mixed tantalum carbide/hafnium carbide matrices, for ultrahigh temperatures and oxidizing environments.

In addition, Ultramet is capable of applying various types of UHTC coatings to different substrates and creating freestanding thick-walled structures by chemical vapor deposition. Deposition materials include:

- Hafnium, zirconium, titanium, tantalum and niobium diborides.
- Hafnium, zirconium, titanium, tantalum and niobium carbides.
- Hafnium, tantalum and boron nitrides.

Chapter 7

Patent Analysis

Chapter 7: Patent Analysis

Introduction

In this section, BCC Research provides an analysis of 106 U.S. patents related to advanced ceramic materials for extreme environments, awarded between Jan. 1, 2018 and April 30, 2020. Patents describe innovations that, in general, fall into one or more of the following categories:

- Materials and compositions.
- Fabrication methods.
- Applications.

All three categories are considered relevant to this study. Patent numbers, issue dates, titles, and assignees for each of these patents are presented in the following pages. Patents have been divided into separate tables according to the issue year.

Some of the most significant patents issued or applied for were previously described in the section entitled "Latest Technological Developments, 2016 to Present". In this section, BCC Research performs a detailed analysis of all these recently awarded patents, with the evaluation organized as follows:

- General trends.
- Trends by country and region.
- Trends by assignee.
- Trends by patent category.
- Trends by material type.
- Trends by material group.
- Trends by application.

Summary of Recently Awarded Patents

The next tables provide a brief summary of all the U.S. patents that were found to be related to advanced ceramic materials for extreme environments (including materials, fabrication processes, and applications), issued since January 2018 (in reverse chronological order).

Table 58
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, 2020

Patent #	Date Issued	Title	Assignee(s)
10,637,015	April 28, 2020	Ceramic materials and seals for high temperature reactive material devices	Ambri Inc. (Cambridge, MA)
10,633,719	April 28, 2020	Gun barrel manufacturing methods	Gunwright Intellectual Properties LLC (Gilbert, AZ)
10,633,292	April 28, 2020	Sintered material and cutting tool including same	Sumitomo Electric Hardmetal Corp. (Itami-shi, Japan)
10,632,542	April 28, 2020	Cutting tool and manufacturing method thereof	Sumitomo Electric Hardmetal Corp. (Itami-shi, Japan)
10,618,845	April 14, 2020	Refractory ceramic product	Refractory Intellectual Property GmbH & Co. KG (Vienna, Austria)
10,597,292	March 24, 2020	Process for generating power and hydrogen gas	King Fahd University of Petroleum and Minerals (Dhahran, Saudi Arabia)
10,593,855	March 17, 2020	Fully integrated thermoelectric devices and their application to aerospace de-icing systems	Pierre L. De Rochemont (Austin, TX)
10,591,230	March 17, 2020	Unitary graphene-based composite material	Global Graphene Group Inc. (Dayton, OH)
10,584,070	March 10, 2020	Ceramic matrix composites having monomodal pore size distribution and low fiber volume fraction	General Electric Co. (Schenectady, NY)
10,581,115	March 3, 2020	Electrolyte for a solid-state battery	Corning Inc. (Corning, NY)
10,577,951	March 3, 2020	Gas turbine engine with dovetail having contoured root	Rolls-Royce North American Technologies Inc. (Indianapolis, IN); Rolls-Royce High Temperature Composite Inc. (Cypress, CA)
10,577,292	March 3, 2020	Hydrocarbon conversion	ExxonMobil Chemical Patents Inc. (Baytown, TX)
10,570,742	Feb. 25, 2020	Gas turbine part and method for manufacturing such gas turbine part	Ansaldo Energia IP UK Ltd. (London, U.K.)
10,566,482	Feb. 18, 2020	Inorganic coating-protected unitary graphene material for concentrated photovoltaic applications	Nanotek Instruments Inc. (Dayton, OH)

Patent #	Date Issued	Title	Assignee(s)
10,563,961	Feb. 18, 2020	Pre-stressed curved ceramic plates/tiles and method of producing same	IMI Systems Ltd. (Ramat Hasharon, Israel)
10,550,303	Feb. 4, 2020	High emissivity materials and methods of manufacture	Purdue Research Foundation (West Lafayette, IN)
10,549,372	Feb. 4, 2020	Brazing compositions for ductile braze structures, and related processes and devices	General Electric Co. (Schenectady, NY)
10,546,661	Jan. 28, 2020	Additive manufacturing technique for placing nuclear reactor fuel within fibers	Free Form Fibers LLC (Saratoga Springs, NY)
10,544,689	Jan. 28, 2020	Hybrid blade for turbomachines	MTU Aero Engines AG (Munich, Germany)
10,538,431	Jan. 21, 2020	Nanolaminated 2-2-1 MAX-phase compositions	Drexel University (Philadelphia, PA)

Source: BCC Research

Table 59
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, 2019

Patent #	Date Issued	Title	Assignee(s)
10,515,728	Dec. 24, 2019	High temperature ceramic nuclear fuel system for light water reactors and lead fast reactors	Westinghouse Electric Co. LLC (Cranberry Township, PA)
10,493,408	Dec. 3, 2019	Two-dimensional metal carbide desalination membrane	Qatar Foundation for Education, Science and Community Development (Doha, Qatar)
10,480,907	Nov. 19, 2019	Ballistic art	Cardinal Technologies LLC (Plymouth, MN)
10,480,403	Nov. 19, 2019	Combustor with adjustable swirler and a combustion system	King Fahd University of Petroleum and Minerals (Dhahran, Saudi Arabia)
10,478,894	Nov. 19, 2019	Carbon as an aide for ductile nanocellular foam	United Technologies Corp. (Farmington, CT)
10,472,976	Nov. 12, 2019	Machinable CMC insert	Rolls-Royce North American Technologies Inc. (Indianapolis, IN); Rolls-Royce Corp. (Indianapolis, IN)
10,472,048	Nov. 12, 2019	Gas turbine engine spinner	United Technologies Corp. (Farmington, CT)
10,465,534	Nov. 5, 2019	Machinable CMC insert	Rolls-Royce North American Technologies Inc. (Indianapolis, IN); Rolls-Royce Corp. (Indianapolis, IN)
10,464,849	Nov. 5, 2019	Fast-densified ceramic matrix composite and fabrication method	Edward J. Pope (Westlake Village, CA)

Patent #	Date Issued	Title	Assignee(s)
10,458,653	Oct. 29, 2019	Machinable CMC insert	Rolls-Royce North American Technologies Inc. (Indianapolis, IN); Rolls-Royce Corp. (Indianapolis, IN)
10,450,808	Oct. 22, 2019	Multi-part superabrasive compacts, rotary drill bits including multi-part superabrasive compacts, and related methods	US Synthetic Corp. (Orem, UT)
10,443,444	Oct. 15, 2019	Cost effective manufacturing method for GSAC incorporating a stamped preform	United Technology Corp. (Hartford, CT)
10,428,417	Oct. 1, 2019	Coated cutting tool	Seco Tools AB (Fagersta, Sweden)
10,415,925	Sept. 17, 2019	Projectile accelerator with heatable barrel	Science Applications International Corp. (Reston, VA)
10,401,028	Sept. 3, 2019	Machinable CMC insert	Rolls-Royce North American Technologies Inc. (Indianapolis, IN); Rolls-Royce Corp. (Indianapolis, IN)
10,400,150	Sept. 3, 2019	High emissivity coating compositions and manufacturing processes therefore	SCG Chemicals Co. Ltd. (Bangkok, Thailand); SIAM Refractory Industry Co. Ltd. (Bangkok, Thailand)
10,399,041	Sept. 3, 2019	Two-dimensional metal carbide antimicrobial membrane and antimicrobial agent	Qatar Foundation for Education, Science and Community Development (Doha, Qatar)
10,378,599	Aug. 13, 2019	Brake rotor with decorative insert	GM Global Technology Operations LLC (Detroit, MI)
10,378,450	Aug. 13, 2019	Chemistry based methods of manufacture for MAXMET composite powders	United Technologies Corp. (Hartford, CT)
10,371,008	Aug. 6, 2019	Turbine shroud	Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies Inc. (Indianapolis, IN)
10,364,193	July 30, 2019	Method for synthesizing high-purity ultrafine ZrC-SiC composite powder	Shandong Ultraming Fine Ceramics Co. Ltd. (Zibo, China)
10,344,369	July 9, 2019	Structure or component for high temperature applications, as well as methods and apparatus for producing same	Airbus Defense and Space GmbH (Ottobrunn, Germany)
10,323,608	June 18, 2019	Combustion system with an ion transport membrane assembly and a method of using thereof	King Fahd University of Petroleum and Minerals (Dhahran, Saudi Arabia)
10,323,339	June 18, 2019	Aircraft brake disc materials and methods	Goodrich Corp. (Charlotte, NC)
10,315,387	June 11, 2019	High content PCBN compact including	Smith International Inc. (Houston, TX)

Patent #	Date Issued	Title	Assignee(s)
10,309,257	June 4, 2019	Turbine assembly with load pads	Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies Inc. (Indianapolis, IN)
10,309,016	June 4, 2019	Method for preparing a carbide ceramics multilayer coating on, and optionally in, a part made of a carbon-containing material using a reactive melt infiltration RMI technique	Commissariat a l'Energie Atomique et aux Energies Alternatives (Paris, France); Centre National de la Recherche Scientifique (Paris, France)
10,308,559	June 4, 2019	Sintered polycrystalline cubic boron nitride body	Element Six Ltd. (Oxfordshire, U.K.)
10,297,879	May 21, 2019	Titanium diboride nanotubes for trapping gases in lithium ion batteries	GM Global Technology Operations LLC (Detroit, MI)
10,285,312	May 7, 2019	Method and apparatus for creating perfect microwave absorbing printed circuit boards	Flextronics AP LLC (Broomfield, CO)
10,281,045	May 7, 2019	Apparatus and methods for sealing components in gas turbine engines	Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies Inc. (Indianapolis, IN)
10,279,578	May 7, 2019	Additive manufacturing of composite materials with composition gradient	Washington State University (Pullman, WA)
10,266,420	April 23, 2019	Method for the generation of power	University of Florida Research Foundation Inc. (Gainesville, FL)
10,265,673	April 23, 2019	Protective leaching cups, leaching trays, and methods for processing superabrasive elements using protective leaching cups and leaching trays	US Synthetic Corp. (Orem, UT)
10,259,158	April 16, 2019	Method and apparatus for fabricating ceramic and metal components via additive manufacturing with uniform layered radiation drying	The Curators of the University of Missouri (Columbia, MO)
10,253,571	April 9, 2019	Rotatively mounting cutters on a drill bit	Halliburton Energy Services Inc. (Houston, TX)
10,252,946	April 9, 2019	Composite ceramic composition and method of forming same	Corning Inc. (Corning, NY)
10,246,945	April 2, 2019	Earth-boring tools, methods of forming earth-boring tools, and methods of forming a borehole in a subterranean formation	Baker Hughes LLC (Houston, TX)
10,273,583	March 30, 2019	Gas turbine engine component coating with self-healing barrier layer	United Technologies Corp. (Farmington, CT)

Patent #	Date Issued	Title	Assignee(s)
10,234,243	March 19, 2019	Antiballistic armor comprising a super-hard strike face	Jacob A. Ganor (Kowloo, Hong Kong)
10,232,441	March 19, 2019	Fabrication of articles from nanowires	United Technologies Corp. (Hartford, CT)
10,224,125	March 5, 2019	Compositions comprising free-standing two-dimensional nanocrystals	Drexel University (Philadelphia, PA)
10,220,462	March 5, 2019	Apparatus for brazing radial bearings and related methods	US Synthetic Corp. (Orem, UT)
10,215,537	Feb. 26, 2019	Modular ceramic composite antiballistic armor	Jacob A. Ganor (Kowloon, Hong Kong)
10,208,542	Feb. 19, 2019	Polycrystalline compacts, earth-boring tools including such compacts, and methods of fabricating polycrystalline compacts	Baker Hughes Inc. (Houston, TX)
10,199,788	Feb. 5, 2019	Monolithic MAX phase ternary alloys for sliding electrical contacts	National Technology & Engineering Solutions of Sandia LLC (Albuquerque, NM)
10,190,434	Jan. 29, 2019	Turbine shroud with locating inserts	Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies, Inc. (Indianapolis, IN)
10,189,746	Jan. 29, 2019	Multi-phasic ceramic composite	Saint-Gobain Ceramics & Plastics Inc. (Worcester, MA)
10,189,709	Jan. 29, 2019	System for cogeneration of power and hydrogen	King Fahd University of Petroleum and Minerals (Dhahran, Saudi Arabia)
10,183,867	Jan. 22, 2019	Leaching assemblies, systems, and methods for processing superabrasive elements	US Synthetic Corp. (Orem, UT)
10,174,578	Jan. 8, 2019	Wellbore isolation devices with degradable slip assemblies with slip inserts	Halliburton Energy Services Inc. (Houston, TX)
10,167,733	Jan. 1, 2019	Turbine engine component with vibration damping	United Technologies Corp. (Farmington, CT)

Source: BCC Research

Table 60
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, 2018

Patent #	Date Issued	Title	Assignee(s)
10,145,258	Dec. 4, 2018	Low permeability high pressure compressor abradable seal for bare Ni airfoils having continuous metal matrix	United Technologies Corp. (Hartford, CT)
10,145,021	Dec. 4, 2018	Apparatus for processing materials at high temperatures and pressures	SLT Technologies Inc. (Los Angeles, CA)
10,144,113	Dec. 4, 2018	Methods of forming earth-boring tools including sinterbonded components	Baker Hughes Inc. (Houston, TX)
10,128,004	Nov. 13, 2018	High temperature strength, corrosion resistant, accident tolerant nuclear fuel assembly	Westinghouse Electric Co. LLC (Cranberry Township, PA)
10,125,549	Nov. 13, 2018	Cutting element support shoe for drill bit	Halliburton Energy Services Inc. (Houston, TX)
10,125,548	Nov. 13, 2018	Drill bits with core feature for directional drilling applications and methods of use thereof	Smith International Inc. (Houston, TX)
10,124,423	Nov. 13, 2018	Rotary cutting tools having adjacent cutting inserts with wave-shaped edges and overlapping rotational trajectories coinciding in phase	Tungaloy Corp. (Iwaki-shi, Japan)
10,124,413	Nov. 13, 2018	Cubic boron nitride sintered body and cutting tool	Kyocera Corp. (Kyoto-shi, Japan)
10,119,728	Nov. 6, 2018	Solar energy collection and storage	Virgil D. Perryman (Sterret, AL)
10,118,143	Nov. 6, 2018	Ceramic orifice chamber for fluid catalytic cracking unit	Total Raffinage Chimie (Courbevoie, France)
10,113,368	Oct. 30, 2018	Cutting elements, earth-boring tools incorporating such cutting elements, and methods of forming such cutting elements	Baker Hughes Inc. (Houston, TX)
10,107,550	Oct. 23, 2018	Crucible materials	Crucible Intellectual Property LLC (Rancho Santa Margarita, CA)
10,107,043	Oct. 23, 2018	Superabrasive elements, drill bits, and bearing apparatus	US Synthetic Corp. (Orem, UT)
10,105,820	Oct. 23, 2018	Superabrasive elements including coatings and methods for removing interstitial materials from superabrasive elements	US Synthetic Corp. (Orem, UT)
10,099,346	Oct. 16, 2018	Methods of fabricating a polycrystalline diamond compact	US Synthetic Corp. (Orem, UT)

Patent #	Date Issued	Title	Assignee(s)
10,094,233	Oct. 9, 2018	Turbine shroud	Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies Inc. (Indianapolis, IN)
10,087,073	Oct. 2, 2018	Nano graphene platelet-reinforced composite heat sinks and process for producing same	Nanotek Instruments Inc. (Dayton, OH)
10,081,577	Sept. 25, 2018	Cubic boron nitride sintered body and coated cubic boron nitride sintered body	Tungaloy Corp. (Iwaki-shi, Japan)
10,077,608	Sept. 18, 2018	Thermally stable materials, cutter elements with such thermally stable materials, and methods of forming the same	Smith International Inc. (Houston, TX)
10,077,214	Sept. 18, 2018	Sintered porous material and filter element using same	Intermet Technologies Chengdu Co. Ltd. (Chengdu, China)
10,040,724	Aug. 7, 2018	Ceramic composite and method to prepare the composite	University of the Witwatersrand (Johannesburg, South Africa); Fraunhofer-Gesellschaft zur Forderung der Angewandten Forschung E.V. (Munich, Germany)
10,037,886	July 31, 2018	Method of manufacturing silicon carbide semiconductor device using graphene and hexagonal boron nitride	Fuji Electric Co. Ltd. (Kawasaki-shi, Japan)
10,035,732	July 31, 2018	Refractory product, batch for producing the product, method for producing the product, and use of the product	Refractory Intellectual Property GmbH & Co. KG (Vienna, Austria)
10,012,100	July 3, 2018	Turbine shroud with tubular runner-locating inserts	Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies Inc. (Indianapolis, IN)
10,011,000	July 3, 2018	Leached superabrasive elements and systems, methods and assemblies for processing superabrasive materials	US Synthetic Corp. (Orem, UT)
10,001,022	June 19, 2018	Seals for gas turbine engine	United Technologies Corp. (Hartford, CT)
9,951,949	April 24, 2018	Ultrahigh energy density and emissivity for energy conversion	Michael H. Gurin (Glenview, IL)
9,951,566	April 24, 2018	Superabrasive elements, methods of manufacturing, and drill bits including same	US Synthetic Corp. (Orem, UT)
9,926,977	March 27, 2018	Bearing elements, bearing apparatuses including same, and related methods	US Synthetic Corp. (Orem, UT)
9,926,794	March 27, 2018	Turbine blade tip treatment for industrial gas turbines	United Technologies Corp. (Hartford, CT)
9,926,197	March 27, 2018	Method and apparatus for producing compound powders	Bo Liu (Spokane Valley, WA); Hongjie Qiu (Milpitas, CA)

Patent #	Date Issued	Title	Assignee(s)
9,919,973	March 20, 2018	Synthesis of high temperature ceramic powders	The Florida International University Board of Trustees (Miami, FL)
9,908,215	March 6, 2018	Systems, methods and assemblies for processing superabrasive materials	US Synthetic Corp. (Orem, UT)
9,884,788	Feb. 6, 2018	Method for producing low porosity nonoxide ceramics	Rutgers, The State University of New Jersey (New Brunswick, NJ); Office of Naval Research (Arlington, VA)

Source: BCC Research

General Trends

Due to the relatively large number of patents issued globally in recent years related to advanced materials for extreme environments, BCC Research has limited its analysis to 106 of the most recent patents, corresponding to a period of approximately two and a half years.

The total number of issued patents increased from an average of 2.8 patents per month in 2018 (corresponding to 34 patents for the entire year) to 5.0 patents per month in 2020 (corresponding to 60 patents for the entire year). The total number of patents for 2020 was extrapolated based on actual figures for the first four months of the year. Since 2018, the number of patents related to advanced ceramic materials for extreme environments has been rising at a CAGR of 32.8%.

Generally speaking, an average of three patents per month or more indicates significant interest in a particular technology. In 2019 and 2020, the average number of patents per month related to advanced ceramic materials for extreme environments has been above this threshold value and rising, showing that interest in AMEE technology is growing rapidly.

The total number of patents issued takes on even more significance if one considers that they refer only to those issued in the U.S.; patents issued in other regions of the world are not included in the total count.

As will be detailed in the following sections, companies and research organizations are very active in developing innovative compositions to achieve improved properties, introducing new or modified fabrication processes to increase throughput, and developing new applications for these products.

The next figure is a graphic representation of patents issued from 2018 through 2020.

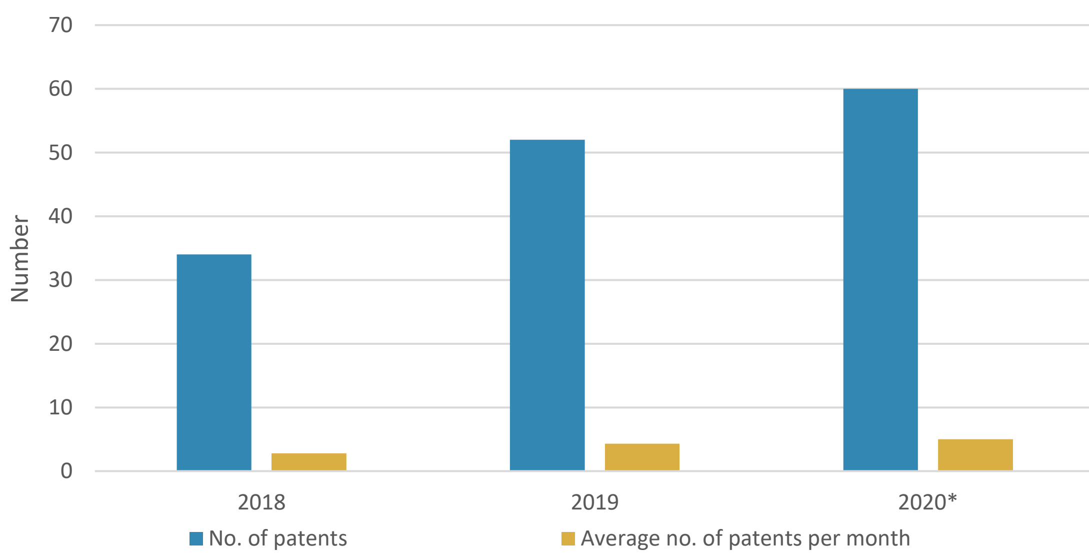
Table 61
U.S. Patent Trends for Advanced Ceramic Materials for Extreme Environments, Through 2020
(Number)

	2018	2019	2020*	CAGR% 2018-2020
No. of patents	34.0	52.0	60.0	32.8
Average no. of patents per month	2.8	4.3	5.0	33.6

(*) The number of patents for 2020 was extrapolated based on data for the first four months of the year

Source: BCC Research

Figure 43
U.S. Patent Trends for Advanced Ceramic Materials for Extreme Environments, 2018-2020
(Number)



Source: BCC Research

Trends by Country and Region

The 106 relevant patents evaluated in this study were awarded to companies, institutions, and individuals located in 13 different countries: Austria, China (including Hong Kong), France, Germany, Israel, Japan, Qatar, Saudi Arabia, South Africa, Sweden, Thailand, U.K., and the U.S.

The U.S. accounts for the largest number of patents with a share of 72.9% of the total. The Asia-Pacific region follows with a share of 10.3%. Companies located in Europe represent a 9.3% share, whereas the Rest of the World accounts for 7.5% of the total.

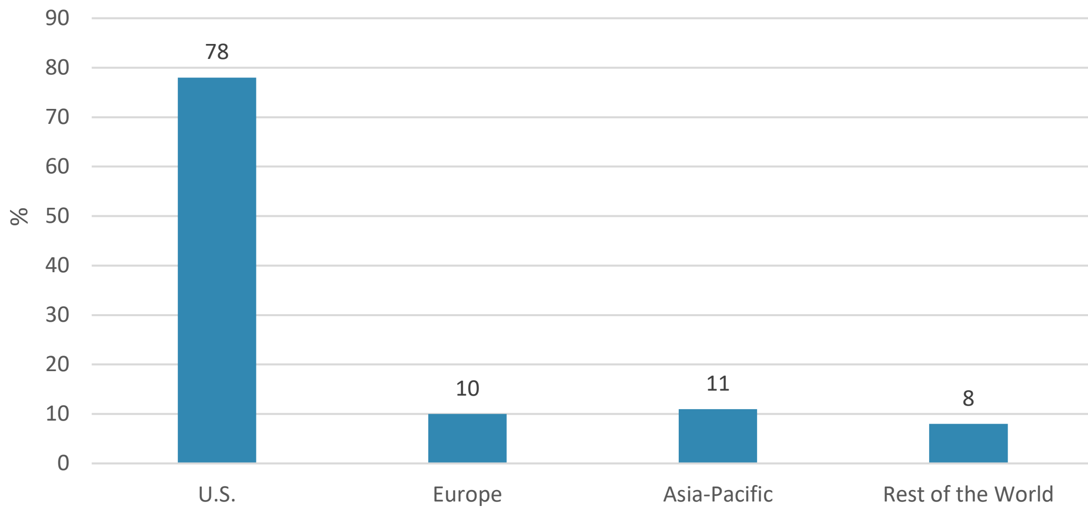
The table and figure below provide a summary of the relative breakdown of patents among various regions. The total number of patents is 107 because one patent was awarded to organizations located in two different countries.

Table 62
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, by Region, 2018-2020
(Number/%)

Region	Patents	
	Number	**% Share**
U.S.	78	72.9
Europe	10	9.3
Asia-Pacific	11	10.3
Rest of the World	8	7.5
Total	107	100.0

Source: BCC Research

Figure 44
U.S. Shares of Patents on Advanced Ceramic Materials for Extreme Environments, by Region, 2018-2020
(%)



Source: BCC Research

The next table and figure show the breakdown of total patents issued by country during the same period.

The U.S. is the leading country in terms of patent issued. The share of patents issued to U.S.-based organizations decreased from 74.3 % in 2018 (corresponding to 26 patents) to 65.0% of the total for the first four months of 2020 (corresponding to 13 patents).

Japan is second in term of patents awarded (6 during the two-year period). For Japanese organizations, the share of patents issued decreased from 11.4% of the yearly total in 2018 (4 patents) to 10.0% of the total for the first four months of 2020 (2 patent).

Saudi Arabia and China share the third place in terms of patents issued, with 4 patents each during the reporting period. For Saudi Arabian organizations the share of patents issued increased from 0% in 2018 to 5 % in 2020.

For Chinese firms, the share of patents decreased from of 2.8% in 2018 (one patent) to nothing in 2020.

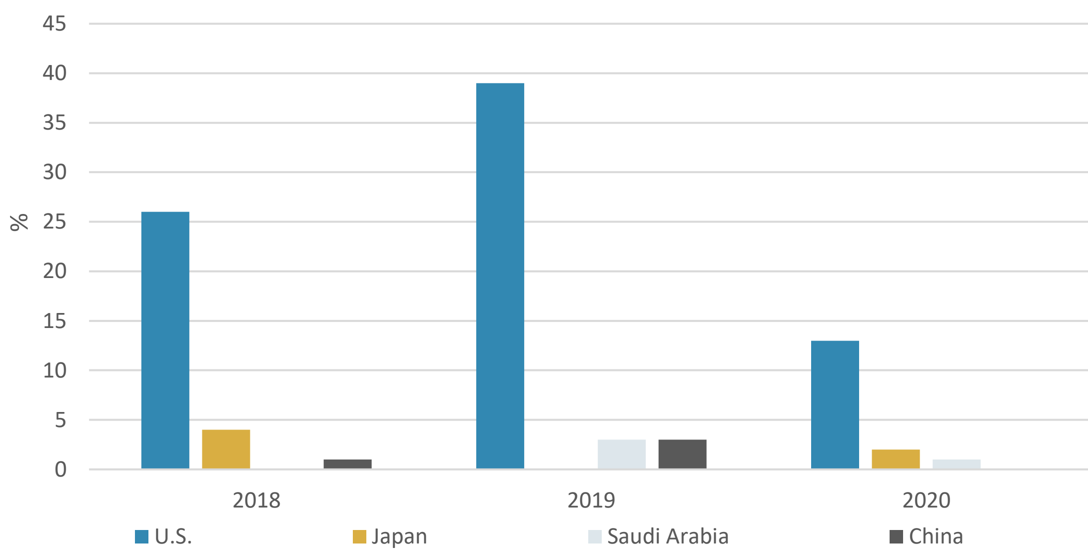
In the remaining nine countries, the share of patents awarded increased from 11.4% in 2018 (4 patents) to 20% in 2020 (2 patents during the first four months), indicating that interest in AMEE technology is overall spreading to different countries other than the top four.

Table 63
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, by Country, 2018-2020
(Number)

Country	2018	2019	2020	Total
U.S.	26	39	13	78
Japan	4	0	2	6
Saudi Arabia	0	3	1	4
China	1	3	0	4
Others	4	7	4	15
Total	35	52	20	107

Source: BCC Research

Figure 45
U.S. Shares of Patents on Advanced Ceramic Materials for Extreme Environments, by Country, 2018-2020
(%)



Source: BCC Research

Trends by Assignee

The next table summarizes the number of patents issued by assignee. The 103 U.S. patents related to advanced ceramic materials for extreme environments were assigned to 54 different organizations, and 8 of them were issued to individuals. In five cases, two assignees filed jointly for the same patent; hence the total count is 111.

Seven organizations (or 13.0% of the total) were awarded three or more patents, accounting for 41.4% of the total patent count.

The leaders are Rolls-Royce (Indianapolis, IN) and US Synthetic (Orem, UT), both of which were issued 11 patents, corresponding to a share of 9.9% of the total patent count (i.e., 19.8% combined). Patents awarded to Rolls-Royce relate to the utilization of carbide- and boride-based advanced materials for extreme environments in the fabrication of components for gas turbines, such as turbine shrouds and inserts for hot sections. These gas turbines are used in aircraft and power production. Carbides consist primarily of MAX phases.

US Synthetic was issued patents related to the following innovations:

- Substrates for bearings based on carbide material.
- Superhard bearings and cutting tools made from boron nitride.
- Earth-boring drill bits for oil and gas exploration.

United Technologies (Hartford, CT) follows with 10 patents awarded since 2018, corresponding to 9.0% of the total patent count. United Technologies' patents focus on the development of MAX phase ceramics for aircraft gas turbine engines. These products include thermal barrier coatings, vibration damping components, and compressor and turbine sections.

Baker Hughes (Huston, TX) and King Fahd University of Petroleum and Minerals (Dhahran, Saudi Arabia) are next with 4 patents each (or 3.6% of the total). Baker Hughes' patents describe the fabrication of boron nitride earth-boring tools for the oil and gas industry.

Patents issued to King Fahd University, instead, relate to the manufacturing of diboride components for power generation systems, such as oxy-combustion, cogeneration, and syngas combustion plants.

Together, these five leading organizations claimed 36.0% of the total patents awarded.

Table 64
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, by Assignee, 2018-2020
(Number)

Assignee	No. of Patents
Organizations	
Rolls-Royce Corp. (Indianapolis, IN); Rolls-Royce North American Technologies Inc. (Indianapolis, IN); Rolls-Royce High Temperature Composite Inc. (Cypress, CA)	11
US Synthetic Corp. (Orem, UT)	11
United Technology Corp. (Hartford, CT); United Technologies Corp. (Farmington, CT)	10
Baker Hughes Inc. (Houston, TX)	4
King Fahd University of Petroleum and Minerals (Dhahran, Saudi Arabia)	4
Halliburton Energy Services Inc. (Houston, TX)	3
Smith International Inc. (Houston, TX)	3
Corning Inc. (Corning, NY)	2
Drexel University (Philadelphia, PA)	2
General Electric Co. (Schenectady, NY)	2
GM Global Technology Operations LLC (Detroit, MI)	2
Nanotek Instruments Inc. (Dayton, OH)	2
Qatar Foundation for Education, Science and Community Development (Doha, Qatar)	2
Refractory Intellectual Property GmbH & Co. KG (Vienna, Austria)	2
Sumitomo Electric Hardmetal Corp. (Itami-shi, Japan)	2
Tungaloy Corp. (Iwaki-shi, Japan)	2
Westinghouse Electric Co. LLC (Cranberry Township, PA)	2
Airbus Defense and Space GmbH (Ottobrunn, Germany)	1
Ambri Inc. (Cambridge, MA)	1
Ansaldo Energia IP UK Ltd. (London, U.K.)	1
Cardinal Technologies LLC (Plymouth, MN)	1
Centre National de la Recherche Scientifique (Paris, France)	1
Commissariat a l'Energie Atomique et aux Energies Alternatives (Paris, France)	1
Crucible Intellectual Property LLC (Rancho Santa Margarita, CA)	1
Element Six Ltd. (Oxfordshire, U.K.)	1
ExxonMobil Chemical Patents Inc. (Baytown, TX)	1
Flextronics AP LLC (Broomfield, CO)	1
Fraunhofer-Gesellschaft zur Forderung der Angewandten Forschung E.V. (Munich, Germany)	1
Free Form Fibers LLC (Saratoga Springs, NY)	1
Fuji Electric Co. Ltd. (Kawasaki-shi, Japan)	1
Global Graphene Group Inc. (Dayton, OH)	1
Goodrich Corp. (Charlotte, NC)	1
Gunwright Intellectual Properties LLC (Gilbert, AZ)	1
IMI Systems Ltd. (Ramat Hasharon, Israel)	1
Intermet Technologies Chengdu Co. Ltd. (Chengdu, China)	1
Kyocera Corp. (Kyoto-shi, Japan)	1
MTU Aero Engines AG (Munich, Germany)	1

Assignee	No. of Patents
National Technology & Engineering Solutions of Sandia LLC (Albuquerque, NM)	1
Office of Naval Research (Arlington, VA)	1
Purdue Research Foundation (West Lafayette, IN)	1
Rutgers, The State University of New Jersey (New Brunswick, NJ)	1
Saint-Gobain Ceramics & Plastics Inc. (Worcester, MA)	1
SCG Chemicals Co. Ltd. (Bangkok, Thailand)	1
SIAM Refractory Industry Co. Ltd. (Bangkok, Thailand)	1
Science Applications International Corp. (Reston, VA)	1
Seco Tools AB (Fagersta, Sweden)	1
Shandong Ultraming Fine Ceramics Co. Ltd. (Zibo, China)	1
SLT Technologies Inc. (Los Angeles, CA)	1
The Curators of the University of Missouri (Columbia, MO)	1
The Florida International University Board of Trustees (Miami, FL)	1
Total Raffinage Chimie (Courbevoie, France)	1
University of Florida Research Foundation Inc. (Gainesville, FL)	1
University of the Witwatersrand (Johannesburg, South Africa)	1
Washington State University (Pullman, WA)	1
Individuals	
Jacob A. Ganor (Kowloo, Hong Kong)	2
Pierre L. De Rochemont (Austin, TX)	1
Michael H. Gurin (Glenview, IL)	1
Bo Liu (Spokane Valley, WA)	1
Virgil D. Perryman (Sterret, AL)	1
Edward J. Pope (Westlake Village, CA)	1
Hongjie Qiu (Milpitas, CA)	1
Total	8

Source: BCC Research

Trends by Patent Category

The patents analyzed in this study belong to one of the two following categories:

- Materials and compositions. More specifically, these patents describe materials and compositions developed for fabrication of advanced ceramic materials for extreme environments, in particular ceramic composites.

- Fabrication methods. These patents describe new processes for producing advanced ceramic materials for extreme environments, variations of traditional production processes, processes to modify and improve characteristics of advanced ceramic materials for extreme environments, and new AMEE configurations.

- Applications. These patents refer to the utilization of advanced ceramic materials for extreme environments in various industry sectors.

As shown in the next table and figure, 70.8% of the total patents describe the utilization of advanced ceramic materials for extreme environments in various applications, 20.7% refer to fabrication processes for these products, and 8.5% to AMEE materials and compositions.

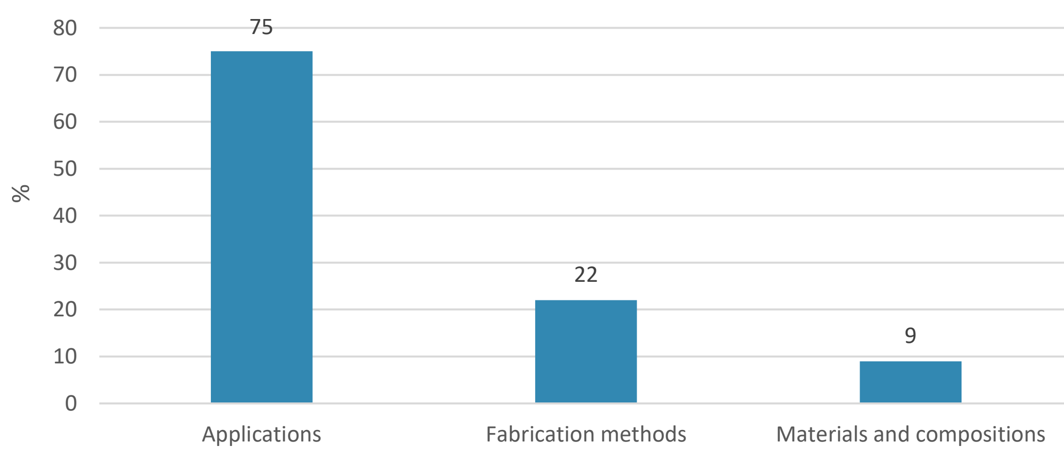
Most R&D activities focus on the utilization of advanced ceramic materials for extreme environments in the energy sector, although new components and their fabrication methods are being introduced for other uses such as aerospace, defense, mechanical, chemical, metallurgical, and electronics as better detailed in the next sections.

Table 65
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, by Patent Category, 2018-2020
(Number/%)

Patent Category	Patents	
	Number	% Share
Applications	75	70.8
Fabrication methods	22	20.7
Materials and compositions	9	8.5
Total	106	100.0

Source: BCC Research

Figure 46
U.S. Patent Shares of Advanced Ceramic Materials for Extreme Environments, by Patent Category, 2018-2020
(%)



Source: BCC Research

Trends by Type of Material

The 106 patents analyzed were divided according to the three main types of materials evaluated in this study:

- Borides.
- Carbides.
- Nitrides.

As shown in the table and figure below, patents referring to nitride-based advanced materials for extreme environments represent the predominant share, at 37.2% of the total. These patents describe primarily the utilization of these ceramics for fabrication of:

- Ultra-hard cutting tools and inserts.
- Wear resistant tools for cutting nickel and cobalt-based alloys.
- Friction stir welding tools.
- Super-hard bearings.
- Crucibles for vacuum induction melting of high purity materials.
- Furnace components for crystal growth.
- Compressor and turbine sections of gas turbine engines.
- Metal-ceramic joints for gas turbine engines.
- Coatings for aircraft turbine blades.
- Antiballistic armor.
- High-energy combustors that generate high-emissivity heat.
- Insulating layers for thermoelectric devices.
- Earth-boring drill bits for gas and oil exploration.
- Coatings for concentrated solar power plants.
- Encapsulation of electronic components as thermal shield.
- Insulating layers for silicon carbide semiconductor devices.
- Heat sinks for electronics.

Carbide-based advanced materials for extreme environments account for the second-largest share of patents at 33.0% of the total patent count. These patents describe the use of these materials for production of:

- Wear-resistant cutting tools and dies.
- Components with high-temperature corrosion resistance and high thermal shock resistance for processing hot fluids in the metallurgical sector.
- Substrates for holding bearings.
- Antimicrobial coatings for preventing biofouling of membranes for wastewater treatment.
- Desalination membranes.
- High-corrosion resistant filters.
- Gas turbine parts.
- Components for hydrocarbon conversion reactors.
- Earth-boring drill bits.
- Fuel assemblies for nuclear reactors.
- Anodes for lithium ion batteries.
- Parts for aircraft gas turbine engines.

Boride-based advanced materials for extreme environments have a share of 29.3% of the total patent count. Patents related to these ceramics refer to their utilization for manufacturing the following products:

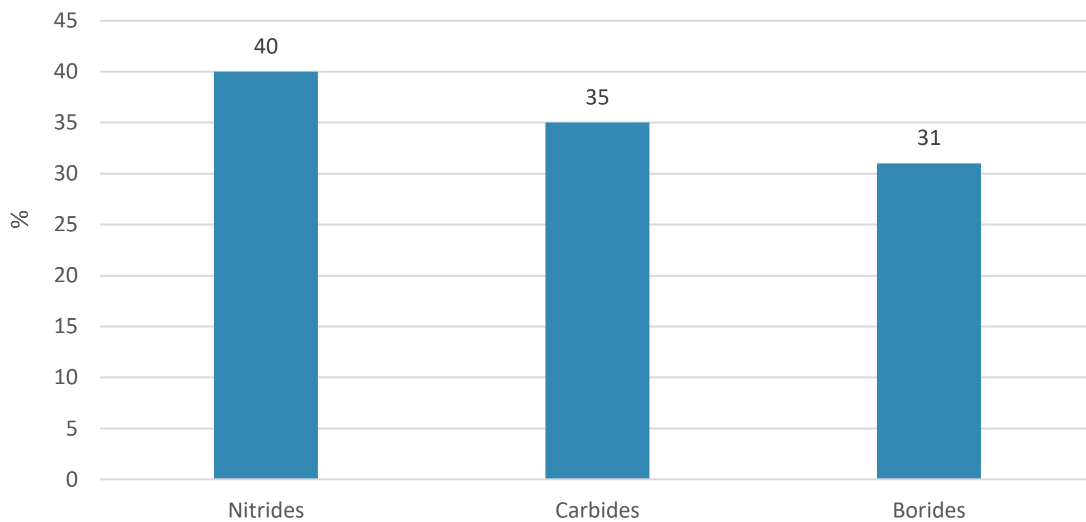
- High thermal emissivity coatings for furnaces and petrochemical plants.
- Components for high-temperature batteries.
- Nuclear fuel assemblies.
- Fuel pellets for nuclear reactors.
- Downhole tools for oil and gas exploration.
- Components for systems that collect solar energy from a wide spectrum of radiations, including infrared.
- Absorbers for solar plants.
- Parts for power generation systems such as oxy-combustion, cogeneration, and syngas combustion plants
- Gas traps for lithium-ion batteries.
- Ballistic protection shields.
- Brake rotor parts for automotive applications.
- Brake discs for aircraft.

Table 66
U.S. Patents Related to AMEE Ceramic, by Type of Material, 2018-2020
(Number/%)

Type of Material	Patents	
	Number	% Share
Nitrides	40	37.7
Carbides	35	33.0
Borides	31	29.3
Total	106	100.0

Source: BCC Research

Figure 47
U.S. Patent Shares of Advanced Ceramic Materials for Extreme Environments, by Type of Material, 2018-2020
(%)



Source: BCC Research

Trends by Material Group

The 106 patents analyzed were also divided according to the three main groups of advanced materials for extreme environments evaluated in this study:

- UHTCs.
- MAX phase ceramics.
- HECs.

As shown in the table and figure below, patents referring to UHTCs represent the predominant share, at 73.6% of the total. These patents describe the utilization of UHTCs for a wide range of applications.

MAX phase ceramics account for 26.4% of the total patent count and introduce primarily carbide-based formulations. These patents refer to the use of these materials for production of:

- Gas turbine components and coatings.
- Joints for components of gas turbine engines.
- Refractories for the metallurgical sector.
- High thermal shock resistant products for metal melting.
- Desalination membranes.
- Antimicrobial coatings for preventing membrane biofouling.
- High-corrosion resistance filters.
- Insulating layers for thermoelectric devices.
- Parts of reactors for hydrocarbon conversion.
- Fuel assemblies for nuclear reactors.
- Anodes for lithium ion batteries.
- Low-wear sliding electrical contacts.
- Free-standing structures for electronics.

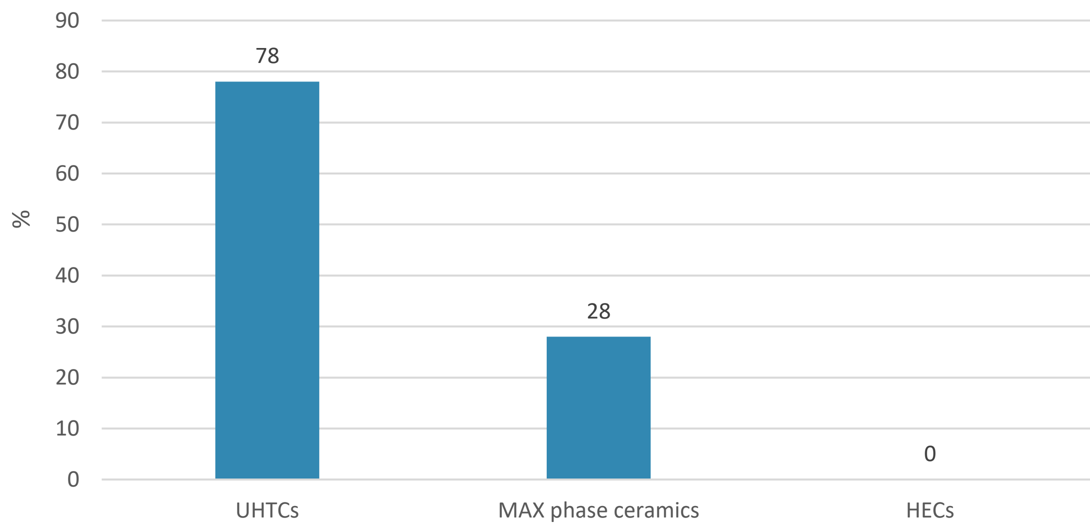
No patent was found related to high-entropy ceramics.

Table 67
U.S. Patents Related to AMEE Ceramic, by Material Group, 2018-2020
(Number/%)

Material Group	Patents	
	Number	% Share
UHTCs	78	73.6
MAX phase ceramics	28	26.4
HECs	–	–
Total	106	100.0

Source: BCC Research

Figure 48
U.S. Patent Shares of Advanced Ceramic Materials for Extreme Environments, by Material Group, 2018-2020
(%)



Source: BCC Research

Trends by Application

The 106 patents analyzed were found to refer to the use of advanced ceramic materials for extreme environments within the following fields of application:

- Aerospace and defense.
- Energy.
- Mechanical/chemical/metallurgical.
- Others (e.g., electronics).

As shown in the table and figure below, patents related to applications of advanced materials for extreme environments in the energy sector represent the largest group at 38.7% of the total. These patents refer to the following topics:

- Fabrication of earth-boring tools and other demanding components for gas and oil exploration.
- Manufacturing of parts for land and industrial gas turbines.
- Joining of components forming large gas turbines.
- Production of high-energy combustors that generate high-emissivity heat.
- Fabrication of parts for hydrocarbon conversion reactors used in the gas and oil industry.
- Manufacturing of fuel assemblies and fuel pellets for nuclear reactors.
- Production of coatings for concentrated solar power plants.
- Fabrication of components for solar energy collection systems.
- Manufacturing of insulating layers for thermoelectric devices.
- Production of anodes, electrolytes, and other components of lithium ion and solid-state batteries.
- Fabrication of components for high-temperature batteries.

Aerospace and defense accounts for the second-largest share of patents at 31.1% of the total. These patents describe primarily the utilization of advanced materials for extreme environments for:

- High-temperature components and thermal barrier coatings for aircraft gas turbine engines.
- Composites for aircraft brake discs.
- Components and coatings for hypersonic and re-entry vehicles.
- Hot structures and functionally graded components for missiles and rockets.
- Multilayer coatings against high temperature oxidation.
- Antiballistic armor.
- Insulation for gun barrels.

Patents related to mechanical/chemical/metallurgical applications represent 23.6% of the total patent count and they describe primarily the use of advanced materials for extreme environments for:

- Crucibles for vacuum induction melting of high purity materials.
- Ultra-hard cutting tools and inserts.
- Friction stir welding tools.
- Super-hard bearings.
- Brake rotor parts for the automotive industry.
- Parts for furnaces for crystal growth.
- Desalination membranes.
- Antimicrobial coatings for membranes for wastewater treatment.
- High-corrosion resistant filters.
- Refractory products for the metallurgical sector.

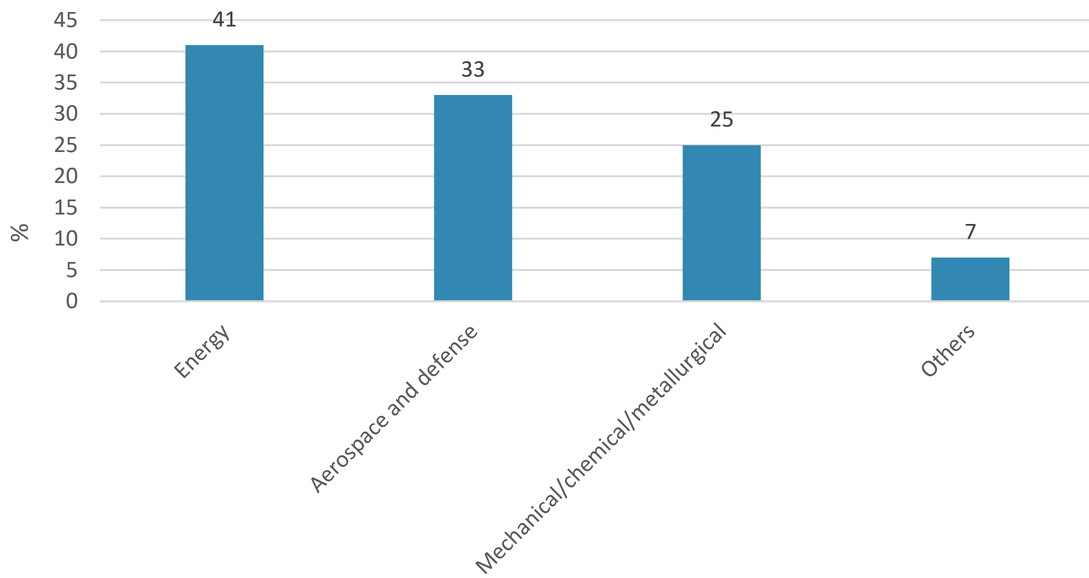
All the remaining applications represent a 6.6% share of the total. These patents describe the utilization of advanced ceramic materials for extreme environments for the fabrication of thermal shield encapsulations for electronics, insulating layers for semiconductor devices, heat sinks, low-wear sliding electrical components, and free-standing structures.

Table 68
U.S. Patents Related to Advanced Ceramic Materials for Extreme Environments, by Application Industry, 2018-2020
(Number/%)

Application Industry	Patents	
	Number	% Share
Energy	41	38.7
Aerospace and defense	33	31.1
Mechanical/chemical/metallurgical	25	23.6
Others	7	6.6
Total	106	100.0

Source: BCC Research

Figure 49
U.S. Patent Shares of Advanced Ceramic Materials for Extreme Environments, by Application Industry, 2018-2020
(%)



Source: BCC Research

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