COMPOSITES UNITED

CERAMIC COMPOSITES

CMC MARKET REPORT

THE GLOBAL MARKET FOR CMC

Manufacturers, OEM, clusters, applications and production volumes

– free short version –

SHORT VERSION

Denny Schüppel

1 General information **8**

1.1 Introduction 8

1.2 Important note on current crisis situations with global impact........ 8

1.3 Data collection procedure........ 9

1.4 Ceramic Matrix Composites: What is meant? 11

1.5 The Ceramic Composites network 18

2 Market players **27**

2.1 Players within the Ceramic Composite........ 27

2.2 Players within Europe 55

2.3 Players USA (+ Canada) 56

2.4 Players in Asia and Australia 56

3 Main applications **57**

3.1 Automotive........ 57

3.2 Aviation 59

3.3 Space 60

3.4 Defence 60

3.5 Engineering........ 60

3.6 Others........ 60

3.7 Possible Future Scenarios........ 60

4 Market volumes **61**

4.1 Introduction........ 61

4.2 Oxide Fiber and Ox/Ox 61

4.3 SiC Fiber and SiC/SiC 62

4.4 C/C 62

4.5 C/SiC........ 66

4.6 Summary 66

5 Summary 68

6 Outlook 69

About Ceramic Composites

The Ceramic Composites is an association of companies and research institutions in the field of ceramic matrix composites.

Our vision for 2030: Ceramic matrix composites will find widespread application as a key component for sustainable production technology in 2030.

Our mission: We promote the industrial use of ceramic matrix composites in mechanical and plant engineering, mobility and the energy industry and support sustainable use. To achieve this goal, we help our members in the targeted acquisition of national projects, the presentation of their capabilities at events and trade fairs, materials marketing and through specific educational offers.

Read more about our goals and our commitment to the development and dissemination of ceramic matrix composites in our position paper. You can read about the potential that ceramic matrix composites already have for the energy transition here (in German).

Research projects of the Ceramic Composites

There are currently several research projects underway that Ceramic Composites has initiated. A brief summary of all ongoing projects is given annually at the Project Forum: The presentations on our projects can be found here.

Working groups of Ceramic Composites

In the Ceramic Composites network, various working groups are active along the entire process chain:

- Finishing CMC Surface Technology CMC/CFRP in cooperation with DKG
- Virtual CMC product development
- Hybrid CMC
- Reinforcement of Ceramic Materials in cooperation with DGM and DKG
- PhD Working Group of Ceramic Composites

Members can find more information, working group documents, material parameters, project databases and more in the internal area on Carbon Connected.

The Authors and Editors

Denny Schüppel studied mechanical engineering at TU-Dresden and INSA Lyon. He worked at Fraunhofer IKTS, Cetex and Daimler AG before joining Composites United in 2014. There, among other things, Denny Schüppel led the project and knowledge management until 2019 and took over the management of Ceramic Composites in 2019. Since then, he has also been co-author of the Carbon Composites Market Report.

Dr. Hagen Klemm: studied chemistry at TU Dresden. Long time he was active in the development of ceramic materials and technologies at Fraunhofer IKTS Dresden in various positions. Currently he works as senior scientist for the Composites United.

Linda Klopsch gained her first practical experience in research and development after studying textile technology at the Fraunhofer Institute for Silicate Research ISC in Würzburg in the field of SiC fiber development. Since 2016, she has been working as an engineer at the German Aerospace Center e.V. in Stuttgart at the Institute of Structure and Design, where she specialized in the development of CMCs. In particular to the research area of textile preforming, ceramic braking systems and engine structures for sounding rockets, especially nozzle assemblies. Since 2018, she has been leading the Component and Material Development Group of the Ceramic Composites and Structures Department. In 2019, she was promoted to head of the department. The research focus of the department, in addition to the manufacturing and development of non-oxide fiber reinforced ceramics, is also on the design and simulation of CMCs within the fabrication and operation in the application. In 2022, she was elected as a member of the Ceramic Composites Executive Board.

Prof. Dr.-Ing. Dietmar Koch: University of Augsburg, head of Chair of Materials Engineering at Institute of Materials Resource Management. He graduated from University of Karlsruhe (now KIT) and did his PhD there in 1994. Then he joined University of Bremen as research assistant and senior scientist and vice head of institute of Advanced Ceramics under guidance of Prof. Grathwohl. In 2011 he became head of department of Ceramic Composites and Structures at German Aerospace Center DLR in Stuttgart and in 2014 vice director of the Institute of Structures and Design. In 2015 he additionally became full Professor at KIT. Since 2019 he is full professor and head of Chair of Materials Engineering and Vice Director of Institute of Materials Resource Management. Since 2007 he is officially head of national working group "Reinforcement of Ceramics" Since 2012 he is Member of Board of Ceramic Composites in Composite United e.V. and since 2021 Chairman of the board. His research focusses on development, characterization and simulation of ceramic matrix composites (CMC) and on resource efficient and sustainable development of CMC.

Michael Kühnel studied Aerospace Engineering at Technical University of Munich (TUM). After professional positions at University of Augsburg (acting for Carbon Composites e.V. where he successfully applied for the funding of the leading-edge cluster MAI Carbon) and the German Aerospace Center (DLR) at its Center for Lightweight Production Technology (ZLP), he joined SGL Carbon in 2018 at its Lightweight and Application Center (LAC). Since 2021 he's in the role of a Data Scientist for its Business Unit Graphite Solutions, where tailored materials and components from Graphite, C/C and C/SiC are made. He published as author and co-author the Carbon Composites Market Report from 2014 to 2018.

Dr. Florian Reichert studied materials science at the University of Bayreuth, later earning his doctorate there with a thesis on the production of ceramic fiber composites with thermoplastic carbon precursors using the LSI process. Since 2016, he has been employed at Schunk Kohlenstofftechnik GmbH in Heuchelheim, where he has been Head of Composites Development since 2018.

Arne Rüdinger studied materials engineering of non-metallic inorganic materials (glass, ceramics, enamels, hydraulic binders) at the Nuremberg University of Applied Sciences. Since 1997 he is working at the Fraunhofer ISC in Würzburg and since 2012 at the Center for High Temperature Lightweight Construction HTL of the Fraunhofer ISC in Bayreuth as a graduate engineer. The work focus is oxide and non-oxide ceramic fibers, coatings and CMC. He is a member of the AK Reinforcement of Ceramic Composites Materials since the early 2000s and

active in Ceramic Composite since its foundation. Since 2018, he is leading the "Ceramic Fibers" working group at the Fraunhofer ISC Center HTL.

Michael Sauer studied materials science at the University of Augsburg. After working at OSRAM AG and Premium Aerotec AG, he currently works as a scientific associate and project manager at Fraunhofer IGCV. He is currently working on a PhD in the field of carbon fiber recycling at the Technical University of Munich. Since 2017, he has also been active for Composites United in the Market Report department and has been the lead author of the annual market report since 2018.

Dr. Clemens Steinborn: Clemens Steinborn studied materials science at TU Bergakademie Freiberg, Germany. Since 2010 he has been working at Fraunhofer IKTS in the field of CMC, fiber coatings and micro mechanical testing. In 2020, he received his PhD from TU Dresden, Germany. His research interests concern material development, processing and characterization of ceramic materials, especially for high-temperature applications.

Dr. Michael Welter: Michael Welter studied ceramics engineering at Hochschule Koblenz before completing a PhD on fiber reinforced inorganic polymers at Victoria University of Wellington, New Zealand. In 2014, he joined the Institute of Materials Research at the German Aerospace Center (DLR) in Cologne working primarily on the materials development and new fabrication technologies for oxide CMC. Since 2020, he is the acting Head of Department "Structural and Functional Ceramics".

1 General information

1.1 Introduction

This is the first edition of the Ceramic Composites Market Report. Is has been published in 2023 and it is planned to publish an update on a regular basis. It gives an overview of current market developments in the field of Ceramic Fibers and Ceramic Matrix Composites (CMC). For this report, information and data were occasionally provided by CU-members or collected by the CU itself, as well as verified and supplemented with the help of external market data.

The Ceramic Composites Network Managment explicitly points out that due to the complex and dynamic market development with individually differing data sources, the information shown here can never provide a completely closed overview of the real market conditions. The aim of the Ceramic Composites Network Managment is to provide an overview of current trends and overarching development-directions based on the sources provided. All information is non-binding and without liability, so that no claims can be made against Ceramic Composites or the Composites United e. V. for the use of the data in the commercial sense.

This report is freely available to members of the network and can be purchased by non-members for 2,400 € + tax. The reason why this report has been produced is the lack of quality of the reports available for purchase to date. The network management is in possession of various reports on CMC. Some of the information contained in these reports is blatantly contradictory. Therefore, the network of Ceramic Composites has decided to create its own report on CMC. This report differs greatly from other reports in terms of data collection. Read more about this in chapter 1.3 Data collection procedure.

1.2 Important note on current crisis situations with global impact

The exact extent and impact of the current crisis sitations on the global CMC market are subject to a persistently volatile data basis at the current level. The very dynamic developments in combination with economic and political measures are difficult to predict in the short term, which influences the reliability of forecasts. This applies in particular with regard to the forecasts shown for specific areas. In this respect, it must be pointed out that the figures, diagrams, and data shown can only represent a possible scenario of further developments. The exact manifestation of the underlying influencing variables must be further investigated in future studies. However, it is of course a clear objective of the CU to achieve the most robust information possible based on the given data. In this respect, attention must be paid to the possible limited comparability of specific statements in individual cases. We are at your disposal for an optimal evaluation and use of the data shown at market.report@composites-united.com.

1.3 Data collection procedure

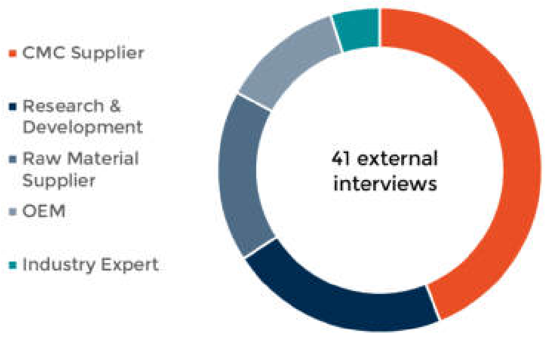
There are several ways to create a market report. One way that has become popular is for large consulting companies to look at industry metrics and try to back-calculate. Other reports rely on building up their information based on their own research on the internet, at conferences or meetings. Furthermore, bottom-up estimates are also made by experts and/or collected with the help of external expert interviews.

All ways of writing a market report have their justification. However, they also have specific disadvantages or advantages that need to be known and understood. For example, the market reports of large consulting companies are often blurred because certain parts of the market can easily be overlooked. On the other hand, these reports are quite easy to compile. With expert interviews or bottum-up estimates, one often has the advantage of being able to look deep into individual processes, but sometimes lateral knowledge is forgotten. In one's own research, one often encounters the obstacle that parts of the CMC market are not transparent, for example due to applications in the military sector.

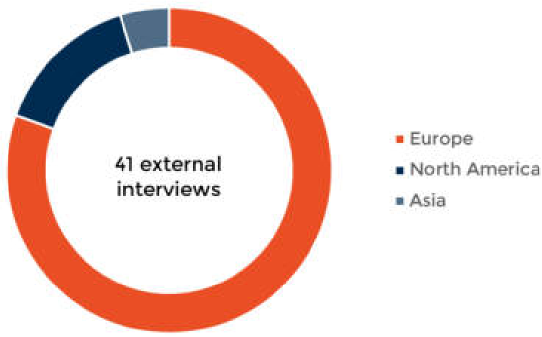
Therefore, the approach taken in this market report is as follows: Only and exclusively contents are included which could be found out via **all the ways** described above. At the same time, the market volumes (and revenues) from several sources must lead to the same result. Some of the ways in which figures were collected are described, some are disclosed due to IP protection. So, it is a mandatory requirement that expert interviews, bottom-up calculations and research results lead to the same result. If this is not the case, then these assumptions have not been included in the report. Sometimes sources were used which are confidential in detail. In sum, however, the overall results may then be published. Of course, the tracing of confidential information must remain excluded.

With this broadly based approach, the authors hope that this market report is significantly more well-founded in what it presents than other market reports that are currently available for purchase. The authors do not claim to have the only truth in the CMC world.

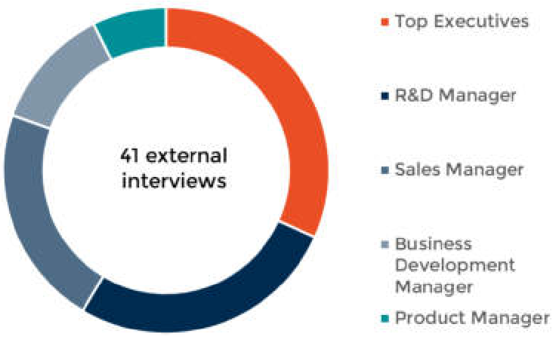
Below you can see an overview of the data sources.



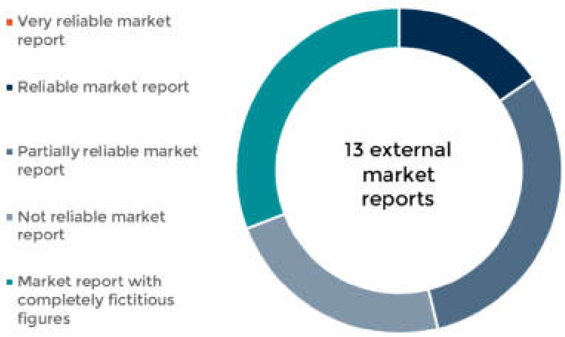
Number of Primary Interviews by Value Chain Node



Number of Primary Interviews by Region



Number of Primary Interviews by Designation



Number of other market studies used as cross-checks

Specifically, the market reports, which did not provide useful results for this report, were left out of the considerations of turnover figures and market volumes.

1.4 Ceramic Matrix Composites: What is meant?

Composite materials are comprised of at least two parts: the reinforcement, which provides special mechanical properties such as stiffness or strength, and the matrix material, which holds everything together. Ceramic matrix composites (CMC) are a special type of composite material in which sometimes both - the reinforcement (refractory fibers) and matrix material - are ceramics (including carbon fibers and carbon matrices). In some cases, the same kind of ceramic is used for both parts of the structure, and additional secondary fibers may also be included. Because of this, CMC are considered a subgroup of both composite materials and ceramics. At the same time, fibers in ceramics usually do not increase strength or stiffness, but often improve damage tolerance and fracture behavior - if properly processed.

Ceramic matrix composites behave much differently from conventional ceramics and are far different from the high-performance metal alloys that used to be implemented. Like ceramics, they are hard and stable at higher temperatures. But they are also very lightweight (one-third the weight of the nickel superalloys they often replace) and possess significantly greater fracture toughness and thermal shock resistance than monolithic ceramics.

There is an extremely wide range of CMC applications, such as: heat exchangers, turbine blades, stator vanes, high-performance braking systems, immersion burner tubes, bulletproof armor, heating elements, etc. The list of applications is growing quickly, too (see chapter 3). CMC components are used in Electrical Engineering, Spaceflight, Aviation, electrical, and electronics industries, just to name a few.

CMC Materials

This market report primarily deals with the following materials: SiC/SiC, Ox/Ox, C/SiC (and C/C-SiC) and C/C.

The reinforcement fiber must exceed a certain length to achieve quasi-ductile fracture behaviour of the CMC. Particle reinforced ceramics are not the focus of this report. Glass or silica fiber-based applications are also not described here.

Silicone Carbide/Silicone Carbide (SiC/SiC): Silicon Carbide (SiC) ceramic matrix composites are composite materials consisting of Silicon Carbide ceramic reinforcing fibers. As a particular type of ceramic matrix composite, SiC/SiC ceramic matrix composites (Silicon Carbide Fiber-Reinforced Silicon Carbide Matrix Composites) show lots of outstanding properties include high temperature capabilities, chemical stability, low density, and resistance to oxidation and corrosion. Based on these advantages, SiC/SiC ceramic matrix composites always used in high-temperature structural applications, such as hot components in gas turbine engines.

Oxide/Oxide (Ox/Ox): Oxide ceramic matrix composites are composite materials consisting of an oxide ceramic reinforcing fibers enbedded in an oxide ceramic matrix. Oxide ceramic matrix composites (Ox/Ox, OCMC or OFC) combine high temperature stability, low density, high strength, and good corrosion resistance with a damage-tolerant fracture behaviour enabling a variety of applications with demanding thermal and mechanical requirements.

Carbon/Silicone Carbide (C/SiC and C/C-SiC): C/SiC or C/C-SiC are fiber composite ceramics made of a carbon fiber and a silicon carbide matrix. The difference in some parts of the world is as follows: C/C-SiC is manufactured using the LSI process, whereas a C/SiC is manufactured using the PIP or CVI process. Mixed processes, such as production first via the CVI route and finally via the LSI route, are listed here under C/SiC. Finally, the matrix of these composites may contain residual carbon or silicon. These materials stand for highest performance and good wear properties. Key figures and market data on the fibers can also be found in the Carbon Composites Market Report.

Carbon/Carbon (C/C): C/C is carbon fiber reinforced carbon. It is also characterised by the highest mechanical performance. On the one hand, C/C can be produced via the CVI route, on the other hand, C/C can be produced by pyrolysis of CFRP with a very carbon-containing matrix, such as phenolic resins or PEEK. These materials are also partly treated of the Carbon Composites Market Report.

Ultra-high temperature ceramic matrix composites (UHTCMC) are a class of refractory CMC, which aspires to overcome the limits associated with currently used C/C and C/SiC in aerospace field as thermal protection systems (TPS) and rocket nozzles. C/C can be used up to 3.000 °C.

On the one hand CMC are lightweight materials with high strength-to-weight ratio even at high temperature, high thermal shock resistance and toughness but suffer of erosion during service. On the other side bulk ceramics made of ultra-high temperature ceramics (e.g. ZrB2, HfB2, or their composites) are hard materials which show low erosion even above 2.000 °C but are heavy and suffer of catastrophic fracture and low thermal shock resistance compared to CMC. Failure is easily under mechanical or thermo-mechanical loads because of cracks initiated by small defects or scratches.

Main CMC Manufacturing Processes

Sintering: In Ox/Ox, the matrix material is currently produced by high-temperature treatment ("sintering") from precursor materials. These precursor materials allow temperatures to be kept lower than the usual sintering temperatures of conventional ceramics, which are around 1,600 °C. The available oxidic fibers would be too damaged by such high temperatures. The starting materials are liquids that are mixed with high proportions of oxide ceramic powders to form a so-called slurry, which is then introduced into the fibers. At temperatures between 1,000 °C and 1,200 °C, the oxide ceramic, porous matrix is formed (associated with strong volume shrinkage). An example of precursor materials are mixtures of Al_2O_3 powder with tetraethyl ortho-silicate (as silicon and oxygen donor) and aluminium butylate (as aluminium donor), which in the right mixture produce mullite as matrix. Other possibilities for the liquids include sol-gel approaches. However, the state of the art are purely aqueous suspensions of powders with nanometre grain sizes, in which a proportion of coarser oxide ceramic powders of various qualities (aluminium oxide, zirconium oxide) is also mixed. Here, the porosity of commercially used material is around 20 %.

Chemical Vapor Infiltration (CVI): This process is based on coating processes in which a specific gas or gas mixture deposits material on heated surfaces. It is called CVD process (Chemical Vapor Deposition). When this process is applied to a fiber structure fixed in component form, the coating material is also deposited on the fiber surfaces inside the component. Therefore, this process is also called Chemical Vapour Infiltration or CVI process. An example of this is a process to produce C/C: a C-fiber structure is gassed with a mixture of argon and methane (CH_4) or propane (C_3H_8) under certain pressure (usually below 100 hPa) and temperature conditions (usually above 1,000 °C). Carbon is deposited from the gas mixture on and between the fibers. Another example is the deposition of silicon carbide. For this, a gas mixture of hydrogen as catalyst and methyl trichlorosilane (MTS, chemical formula CH_3SiCl_3) is usually used, which also plays a role in the production of silicones. The carbon and silicon atoms of the MTS molecule form silicon carbide on any surface hotter than about 800 °C, the remaining H and Cl atoms leave the process as HCl gas with the hydrogen. Closed pores are necessarily formed during deposition when gas access openings are overgrown.

Melt Infiltration / Liquid Silicon Infiltration (LSI): In this process, a material is already present between the fibers, which is transformed into the desired ceramic matrix by chemical reaction with another substance. A wellknown method applied for various materials is the reaction of porous carbon with liquid silicon to form silicon-containing silicon carbide, so-called SiSiC. A typical example that has been industrially introduced in the production of ceramic brake discs is the conversion of the matrix carbon of a porous C/C material with liquid silicon. With controlled process control under vacuum and above the melting temperature of the silicon (1.450 °C), essentially the matrix carbon reacts to form silicon carbide and the fibers remain virtually untouched, allowing them to fulfil their reinforcing function. This process is usually referred to as Liquid Silicon Infiltration, abbreviated LSI process. With these processes, the residual porosity is at low values of less than 3 %. A second example of the production of oxide CMC with this process is the so-called directional melt infiltration: molten aluminium between the fibers is oxidised by the addition of oxygen to the aluminium oxide matrix. Alloying components in the melt prevent the continuous oxidation from being interrupted by the formation of aluminium oxide barriers. The finished material still contains residual unreacted aluminium.

Polymer infiltration & pyrolysis (PIP): In this process suitable polymers (hydrocarbons, carbosilanes or carbosilazanes) were pyrolyzed with volume loss and outgassing in a thermal process forming a carbon-, SiC- or SiCN matrix. Fibers, fiber fabrics or fiber fabric stacks and three-dimensional fiber structures can be impregnated or infiltrated with these polymers. Subsequent curing and pyrolysis fix the structure in a first stage. Due to volume shrinkage, the matrix still has a high porosity in this stage, which is not acceptable for most applications. Therefore, to lower the porosity, five to eight (sometimes just four or more than eleven) subsequent cycles of impregnation, curing and pyrolysis are usually required to complete the body-in-white. The process is usually referred to as Liquid Polymer Infiltration, abbreviated to LPI process, and sometimes Polymer Infiltration and Pyrolysis, abbreviated to PIP process.

Again, there is residual porosity as each polymer shrinks in volume during pyrolysis. The porosity reduces with each infiltration and pyrolysis cycle.

Fibers for CMC

SiC-Fibers: Silicon carbide fibers are fibers with a diameter of 5 to 150 micrometres (mostly around 7 - 12 µm) that consist mainly of silicon carbide molecules. Depending on the manufacturing process, they may contain some excess silicon or carbon or a small amount of oxygen. Compared to organic fibers and some ceramic fibers, silicon carbide fibers have high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made silicon carbide fibers the first choice for hot section components in the next generation of gas turbines, such as General Electric's LEAP engine.

There are several processes for manufacturing silicon carbide fibers. The process with the longest experience, invented in 1975 and referred to as the Yajima process, uses a preceramic liquid polymer injected through a spinneret to produce solidified green (unfired) fibers that undergo a series of processing steps, including considerable time in high-temperature furnaces, to convert the polymer to the desired SiC chemistry. These fibers are typically less than 20 microns in diameter and come as twisted strands of more than 300 fibers. Several companies use a variation of this technique, including Nippon Carbon (Japan), Ube Industries (Japan) and the NGS consortium in the US. Fibers produced by this method are the most used fibers in the applications currently performed.

A second approach uses chemical vapour deposition (CVD) to form silicon carbide on a central core of another material while the core passes through a high-temperature reactor. The developed silicon carbide deposit resulting from the vapour phase CVD reaction builds up on a carbon core with a columnar microstructure. The fiber has a relatively large diameter of about 80 to 140 micrometres.

Laser-driven CVD (LCVD) is a related process that uses multiple laser beams as the energy source for the gas-phase reaction, with the key difference that the fibers are grown in their shape rather than on a core structure. The LCVD fibers are produced in a parallel arrangement as each laser beam corresponds to a deposited fiber, with growth rates from 100 microns to over 1 millimetre per second and fiber diameters from 20 to 80 microns.

Almost all the silicon carbide fibers produced are used as fiber reinforcement material in ceramic matrix composites, such as SiC/SiC, a high-temperature composite material for aerospace applications.

Enclosed you will find a rough overview of the currently commercially available fibers (source: data sheets). There are also textile semi-finished products for sale, the data can be obtained from the manufacturers.

Manufacturer	type	Diameter	Density	Strenght	Modulus	Price
Nippon Carbon	Hi-Nicalon "S"	≈ 12 µm	3.1 g/cm³	≈ 2.6 GPa	≈ 420 GPa	≈ 7,000 €/kg
	Hi-Nicalon	≈ 14 µm	2.7 g/cm³	≈ 2.8 GPa	≈ 270 GPa	≈ 3,400 €/kg
	Nicalon NL-200/201	≈ 14 µm	2.6 g/cm³	≈ 3.0 GPa	≈ 220 GPa	≈ 1,100 €/kg
UBE Industries	Tyranno SA 4	≈ 7 - 10 µm	3.1 g/cm³	≈ 2.8 GPa	≈ 380 GPa	≈ 7,000 €/kg
	Tyranno ZMI	≈ 11 µm	2.5 g/cm³	≈ 3.4 GPa	≈ 200 GPa	≈ 1,500 €/kg
	Tyranno LoxM	≈ 11 µm	2.5 g/cm³	≈ 3.3 GPa	≈ 190 GPa	≈ 1,200 €/kg
	Tyranno S	≈ 11 µm	2.4 g/cm³	≈ 3.3 GPa	≈ 170 GPa	≈ 1,000 €/kg
COIC	Sylramic iBN	≈ 10 µm	3.0 g/cm³	≈ 3.0 GPa	≈ 170 GPa	≈ 11,000 €/kg
	Sylramic iBN	≈ 10 µm	2.9 g/cm³	≈ 2.7 GPa	≈ 170 GPa	≈ 9,000 €/kg

There are other suppliers, such as Speciality Materials or Tisics. However, these fibers differ from the fibers mentioned above in that they always have a core (carbon or tungstun wire).

Furthermore, the company BJS Ceramics is currently working together with the Fraunhofer ISC-HTL on the market launch of a SiC fiber from Europe.

General Electric has successfully built up its own in-house fiber production for its own SiC/SiC products in recent years. The production capacity of this in-house plant significantly exceeds the total global product input capacity of other manufacturers. More information can be found in chapter 4.3.

Oxide Fibers: In principle, the only oxidic ceramic fibers available on the market are those based on aluminium oxide and fibers containing additional silicon dioxide in varying proportions and sometimes with additional boron oxide or zirconium oxide. Mixed oxide fibers made of 85 % Al_2O_3 and 15 % SiO_2 are also called mullite fibers. All these fibers are polycrystalline.

Spinning masses are used as starting materials in which organic polymers such as polyvinyl alcohols or polyethylene oxides ensure spinnability. In most cases, salts dissolved in water or colloidally dissolved inorganic components (brine), sometimes supplemented by the addition of very fine powders, are used after drying the spun fiber to produce the so-called green fiber. These are transformed - like so-called green bodies of normal ceramics - by a sintering process into the finished oxidic ceramic fiber.

Manufacturer	type	Diameter	Density	Strenght	Modulus	Price	Composition [%]
3M™	Nextel™ 312	≈ 8 - 12 µm	2.8 g/cm³	≈ 1.6 GPa	≈ 150 GPa	≈ 250 €/kg	62.5 Al_2O_3 24.5 SiO_2 13 B_2O_3
	Nextel™ 440	≈ 10 - 12 µm	3.0 g/cm³	≈ 1,8 GPa	≈ 190 GPa	≈ 500 €/kg	70 Al_2O_3 28 SiO_2 2 B_2O_3
	Nextel™ 610	≈ 11 - 13 µm	3.9 g/cm³	≈ 2.8 GPa	≈ 370 GPa	≈ (300 - 800) €/kg	> 99 Al_2O_3
	Nextel™ 720	≈ 12 - 14 µm	1.9 g/cm³	≈ 2.1 GPa	≈ 250 GPa	≈ (500 - 800) €/kg	85 Al_2O_3 15 SiO_2
Nitivy / Hiltex	ALF FB3	≈ 10 µm	3.0 g/cm³	≈ 1.8 GPa	≈ 190 GPa	-	70 Al_2O_3 28 SiO_2 2 B_2O_3
	ALF F2	≈ 7 µm	2.9 g/cm³	≈ 1.8 GPa	≈ 190 GPa	-	72 Al_2O_3 28 SiO_2
	ALF E3	≈ 10 µm	2.9 g/cm³	≈ 1.7 GPa	≈ 200 GPa	≈ 1,200 €/kg (woven fabric)	80 Al_2O_3 20 SiO_2
	ALF D3*	≈ 10 µm	3.1 g/cm³	≈ 1.7 GPa	≈ 200 GPa	under developmet	85 Al_2O_3 15 SiO_2
	ALF Dc3*	≈ 10 µm	3.3 g/cm³	≈ 1.6 GPa	≈ 240 GPa	under developmet	85 Al_2O_3 15 SiO_2

ALF B2*	≈ 7 µm	3.2 g/cm³	≈ 1.4 GPa	≈ 190 GPa	under devel-opmet	95 Al_2O_3 5 SiO_2
ALF A3*	≈ 10 µm	3.8 g/cm³	≈ 2.2 GPa	≈ 370 GPa	under devel-opmet	> 99 Al_2O_3
ALF A2*	≈ 7 µm	3.8 g/cm³	≈ 2.2 GPa	≈ 370 GPa	under devel-opmet	> 99 Al_2O_3

For high-performance oxide CMC (OFC or O-CMC), Nextel™ 610 and 720 are used almost exclusively. There are or have been other suppliers such as Nitivy, Mitsui, CeraFib or Sumitomo. Mitsui, CeraFib and Sumitomo have left the market. Nitivy is currently working on the development of fibers with an Al_2O_3 content of 85 % and 99 % and would like to enter the market. However, these fibers currently play a minor role on the global CMC market yet, that might change once the ALF B2, ALF Dc3 or ALF A2/A3 from Nitivy are on the market.

At the same time, the German-Austrian company Rath is developing in partly co-operation with Fraunhofer ISC-HTL various oxidic fibers, which should be commercially available in the mid-2020s and compete with the Nextel™ 610 and 720. Saint Gobain in France is also working on its own oxide fibers, in close cooperation with the DITF in Denkendorf. For more information, see chapters 2.2 and 4.

Carbon Fibers: Everything there is to know about carbon fiber can be found in the Carbon Composites Market Report.

1.5 The Ceramic Composites network

Ceramic Composites was founded in 2008 as an association of research institutions and industrial enterprises. Today it is part of the globally active network Composites United e. V. and focused on enabling leading technologies for energy, climate, and mobility with the help of Ceramic Matrix Composites (CMC).

Research projects on CMC are continuously funded in Germany, although to an extent that lags far behind American, Asian, or even French research programs. Nevertheless, the members of Ceramic Composites have achieved a leading research position compared to other countries. The task now is to accelerate the transfer of knowledge and technology and to stimulate commercial implementation in industry.

Experiences show that product implementation for CMC is associated with high technical and economic risks. SME are often unable to master these challenges on their own. Leading German companies and research institutions have therefore organized themselves in the network to jointly push forward the material class of CMC and establish sustainable solution concepts for the economy, energy, climate, and mobility.

Facing Challenges: The fact that global challenges also require major efforts at the national level can be clearly seen in the German Federal Government 's programs. The necessities arising from the climate change, the growth of the world 's population and the increasing shortage of resources are leading to long-term development strategies in Germany, such as the energy transition and mobility transformation, the EU Green Deal and the hydrogen economy. Alongside a sustainable shaping of the ecological and economic future, the high economic strength of the German market must also be secured, not least through its own disruptive leap innovations. This also requires, in some cases inevitably, new material approaches and solutions, such as those that can be implemented through the application of Ceramic Matrix Composites.

The decarbonization of the energy and mobility sectors is of crucial importance for our future development. Regeneratively and sustainably produced in best case green hydrogen and its derivatives are said to have great potential as energy carriers on the way to a zero-emission mobility as well as for the generation of electricity and process heat. For this purpose, many subprocesses require thermal conversion processes, e.g., syngas synthesis, whose efficiencies increase significantly with increasing process temperature. At this point, CMC contribute new and improved key components due to their high temperature resistance and their high stability against aggressive media.

The material class of Ceramic Matrix Composites creates also effective contributions in the transformation of mobility. For engines in modern aircrafts, as well as for high-performance powertrains, in heavy duty vehicles and ships, CMC components constitute a multiplier for the added value chain, as they usually determine the performance of the larger overall system. In addition, CMC offer a high and synergistic cross-sectional effect in the entire field of production technology, chemical process engineering, the thermo-based primary industry as well as in mechanical and plant engineering. At various points in the process and manufacturing environments, Ceramic Matrix Composites can help to increase efficiency, save resources, reduce emissions, and extend life cycles. Derived new production processes and products, also by consequently using the opportunities of digitalization, can strengthen and further expand the production location Germany and gain a new level of competitiveness. This applies to CMC per se, as well as to the corresponding innovative processes and products.

Competing Countries, such as China, Japan, France, or the USA, are clearly promoting the development of this class of materials due to the enormous potential of Ceramic Matrix Composites. Despite this, Germany has achieved a leading research position worldwide in the field of Ceramic Matrix Composites. Now the task is to turn this leading role into a leading market position. The Ceramic Composites network with its German-wide alliance of members wants to contribute to this and sees its task in the industrial as well as the political-social environment.

Access to solutions: The allocation of high-performance key components is one of the strengths of Ceramic Matrix Composites. They can significantly determine the performance and environmental profile of entire technical systems and processes as well as significantly increase the final added value.

What CFRP means for aircraft structures, CMC means for aero-gas turbines: Whether liners, shrouds, blades or nozzles, CMC components reduce weight, allow higher gas temperatures, and save cooling power - all in all, this means lower fuel consumption and a corresponding reduction in CO_2 emissions. Thereby, it will be possible to achieve the climate protection policy goals of the German government for an environmentally friendly air traffic (Flightpath 2050) with a reduction of 40 % CO_2-equivalent by the year 2030.

In this specific case, the use of SiC/SiC-CMC leads to an increase in the combustion temperature of aero-gas turbines to approx. 1,300 °C. As a result, and due to the simultaneous reduction in component weight (- 40 %), efficiency is improved by approx. 5 %. As an example, this leads to a reduction in CO_2 emissions of several megatons per year for the fleet of a major airline. Even without increase of temperature there is already a huge saving of CO_2 emissions due to lower weight of SiC/SiC parts and due to reduced need of cooling air. United States-based General Electric has already positioned CMC-technology for aircraft gas turbines on the market and is preparing for large-scale production. Europe, and Germany in particular, are lacking far behind in this respect.

If this strategic area is not to be left to foreign competitors, and in the future also to China, actions beyond the current framework must be implemented by industry and politics. Technology for stationary gas turbines at all power levels would also benefit from developments for aero engines. As the use of hydrogen becomes more widespread, hydrogen-containing fuel gas for stationary gas turbines will also become inevitable.

Even though gas turbines are currently seen as a bridging technology, they will continue to be needed in the future to balance the fluctuations of renew-able energy sources and to provide large local power volumes during sector coupling and the use of renewable gases. Future gas turbines will require, above all, a high degree of operational flexibility for rapid start-up in just a few minutes, for high operating cycles in hourly changes, and for different fuel mixtures with hydrogen.

Fiber ceramics with their low mass, high thermal shock resistance and chemical high-temperature stability are a predestined material for key components in the hot gas sector.

Hydrogen will be an indispensable energy carrier in the future. In addition to hydrogen production by electrolysis using regenerative electricity (green hydrogen), hydrogen production from biogas and, for a limited time, also from fossil energy carriers by reforming (grey hydrogen) will also be important due to sector coupling. On the one hand, it will be used for direct hydrogen production and, on the other hand, to produce derivatives (power-to-gas), such as synthesis gas, amongst others as a raw material for the chemical industry. Particularly in the case of dry reforming, process efficiency can be increased considerably, to as much as 70 %, by higher process temperatures of above 1,000 °C.

However, metallic reactor tubes are no longer suitable for this purpose – this is where CMC turn out to be the winner. They allow the high reforming temperatures and sustainable safe plant operation. Thus, high-temperature dry reforming would become a powerful component of the hydrogen economy for all types of hydrogen conversion, such as power-to-chemicals, power-to-fuel including re-powering in gas-fired power plants or fuel cells.

Likewise, in the area of so-called ‚new mobility‘, CMC can provide solutions for high-speed aircrafts and urban air transport, such as impact-resistant outer skin or protective covers for infrared sensors or cameras.

Future mobility concepts for passenger transport will rely exclusively on electric drives using batteries or fuel cells. In road-based heavy-duty transport and shipping, internal combustion engines are not yet obsolete in the medium term. Here, modern gas and hydrogen engines can offer a solution on the path to ‚green‘ drives. The Deutz company, for example, is developing high-performance hydrogen engines for stationary operation. Since the direct combustion of hydrogen severely damages conventionally designed engines through hydrogen embrittlement and lubricant destruction, Ceramic Matrix Composites would be a groundbreaking solution for the future. In addition to thermal and mechanical damage tolerance, they provide the possibility of low friction and self-lubricating properties achieved through surface functionalization.

In the entire field of production technology, from the chemical industry to mechanical and plant engineering, Ceramic Matrix Composites can be valuable enablers for improving energy efficiency, saving primary energy, reducing emissions, increasing process reliability, and extending plant availability and service life. Thus, for example, for the thermo-processing technology

- Charging racks,
- CMC-reinforced pipes,
- troughs and vessels for metal casting,
- thermal isolation aprons in steel production,
- ceramic rolling dies,
- molds for glass production or
- burner nozzles in furnace construction

are just a few of existing and future examples from a wide range of possible applications. A completely new development would be, for example, machining tools made of CMC. Tool manufacturers are increasingly feeling the consequences of raw material shortages concerning the special metal Co for WC-Co cutting inserts.

Here, a specially designed Ceramic Matrix Composites material could trigger a material revolution.

In the aerospace sector, where Germany is one of the world‘s technological drivers, CMC are state of the art, e.g. for heat protection systems and for movable control flaps. Micro-launchers, mini rockets and drones are applications that are currently showing rapid market growth and open up new product opportunities for many startups and established companies. CMC offer solutions that have not yet been implemented in terms of thermal and mechanical protection, re-usability or spectral transmission and reflection properties. Particularly the aspect of reusability will be of special importance here.

The same applies to containments made of CMC. For electronic housings, battery and accumulator housings or fuel cell confinements, their non-flammability combined with electrical insulation properties can provide greater safety, for example in the critical sector of aircraft technology.

In principle, containers made of CMC are also suitable for the safe and long-term storage of environmentally critical waste. This offers new concepts for the long-term storage of nuclear waste, which make use of the high chemical stability of Ceramic Matrix Composites. Leakage due to corrosion (also in the planned storage sites) and contamination of the environment or groundwater would be completely ruled out - however, CMC storage containers have not been testet under real-life conditions yet.

For years, the lightweight properties of CMC have been used in braking systems. CMC brakes are corrosion resistant, require little maintenance and are highly effective. Future CMC (or CMC-hybrid) brake discs will save weight and improve emergency braking characteristics in electric and rail vehicles. As recent studies have shown, CMC brakes also significantly reduce the generation of particulate matter, since on the one hand no corrosion products are released and on the other hand the abrasion by volume is lower than with metallic products.

Joint Action: Ceramic Matrix Composites are high-performance materials with strategic importance for a large part of the application potential described. An energy transition without high-temperature lightweight design with CMC will only be partially successful. For a large number of the producing industries, synergistic effects offer an additional economic effect. However, there is still a lot to be done until then. A number of challenges remain unsolved, from fundamental questions of material behavior to logistical issues of fiber supply.

Currently, the availability of large quantities of endless ceramic fibers for reinforcement is not given. Series production of different high-quality ceramic fibers within Germany is just starting. Consequently, there is a substantial dependence on manufacturers in the USA and Japan, some of which are already bound by exclusive contracts with non-European users. In the meantime, several fiber pilot plants, and recently also series production plants, are in operation in Germany, in which prototype fibers of very high quality are produced. However, industrial series production for the wide range of CMC is still pending.

Overall, the high cost of CMC products is blocking wider use of these materials, especially for cost-sensitive applications. This is not only due to the high purchase prices of the fibers, but also to the entire component manufacturing including production yield. The production of CMC is partly not designed for large volume flows. Automation and innovative process technologies can provide important progress here. The formation of a German supply chain to enable consistent quality at moderate costs represents a key challenge in this area, which could significantly reduce the entrepreneurial risk of a product pioneer.

Digitally controlled processes, networking of processes to digitally controlled process chains or even cross-company interlocking are not yet developed in the CMC value network. The participating SME in particular lack the capacities to permanently win the international competition on their own. For material-adapted and digitally supported component design and engineering, there is a lack of consistent material data, knowledge of service life and failure behavior, joining technology and design methods. The simple transfer of procedures and knowledge from other material classes is largely not possible. For the development of new applications, the targeted development and manufacture of demonstrators up to prototypes would help to gain field experience, demonstrate performance and thus increase recognition.

This must be complemented by recycling concepts including repair and re-use of high-quality CMC components, which demonstrate the required level of sustainability (LCA and capability for circular economy). Since CMC are a young class of materials taught in materials science courses, adequate training must be made available to young scientists, engineers and technicians to familiarize them with CMC, to teach them the material-specific characteristics and to convince them to apply CMC. In addition, it must be ensured that the interlinking of science and industry continues to progress in order to intensify the transfer of technology and knowledge to companies and to overcome skepticism about this high-performance class of materials.

Research projects concerning Ceramic Matrix Composites are and have been continuously funded in Germany and the EU, although to an extent that remains far behind American or Asian research programs. Nevertheless, compared internationally, Germany has achieved a leading research position.

So far, the experiences from the Ceramic Composites network show that product implementation for CMC is bound with high technical, but also economical risks. Individual companies, especially SME, are not in a position to master the above-mentioned challenges on their own. The leading companies and research institutes have therefore organized themselves in the Ceramic Composites network in order to make their common interests in the industrial application of CMC heard and take joint action.

Based on the experiences and assessments from the Ceramic Composites members network, the following activities could lead to an intensified utilization of the potentials of CMC:

- Creating the possibility of financing for the commercialization of the internationally recognized know-how available in the German research sector for the production of ceramic fibers. This could be achieved by a larger industrial consortium, which would receive facilitating framework conditions from the federal economic funding.
- Increased research funding with a focus on production technology, design and engineering, efficiency and sustainability with the objective of large collaborative projects in which several CMC manufactures and users form a coalition with the aim of jointly generating and sharing knowledge.
- The establishment of a national demonstration center for CMC applications, in which components are manufactured and tested under realistic conditions. The sponsors of this demonstration center would be the federal government or a federally owned institution as well as industrial companies.

This would directly and indirectly create jobs and, above all, safeguard cutting-edge technology in Germany.

Common Benefit: If it succeeds to establish the material class of CMC in strategic as well as in broad applications, CMC can make a central contribution to the global challenges faced by climate policy, society and the economy. The German industry is thus reestablishing the technological connection to competing countries (e.g. China, USA, France, Japan). The members of the Ceramic Composites Network are striving for global technological leadership in CMC. For this purpose, the SME, LE and R&D institutions participating in the network want to expand their international market position and develop into technology leaders. A strong and established SME industry is digitally crosslinked and works in partnership with LE and R&D institutions. By significantly reducing the manufacturing costs of CMC, this class of materials is also making a breakthrough in new industries and markets. With the help of CMC, German core technologies such as aerospace, energy technology and mechanical and plant engineering can become more future-proof and competitive. By securing and creating jobs in Germany over the long term, a contribution is made to Europe‘s economic sovereignty. Germany can strengthen its global pioneering role in the energy transition by enabling CMC to make key technologies of transition more efficient.

2 Market players

Chapter 2 lists most of the active research institutes and industrial companies that are active in the CMC market. They are sorted by Ceramic Composites members, other European players, players in North America and players in Asia.

2.1 Players within the Ceramic Composite

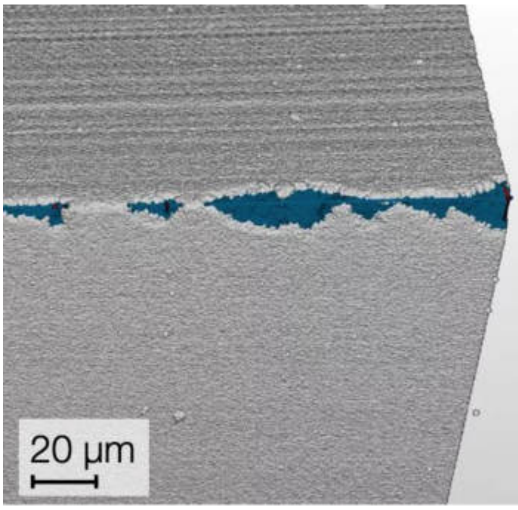
Augsburg Technical University of Applied Sciences, HSA_comp Composite Process Technology: The Composite Process Technology department, led by Prof. Dr.-Ing. Ralf Goller is part of the HSA_comp research group which comprises several teams investigating composites in mechanical engineering. Prof. Dr.-Ing. Ralf Goller and his team are primarily focused on the process and technology development of new materials such as CFRP and CMC with a strong emphasis on practical applications. This involves optimizing machining processes and developing and testing new cutting-edge technologies. The team's particular expertise lies in the 5-axis finishing of ceramics and CMC, with a focus on improving efficiency and quality while considering sustainability. Overall, the Composite Process Technology department is at the forefront of research in this field, developing new materials and methods that promise to advance the state of the art in composite processing.

Core fields of research:

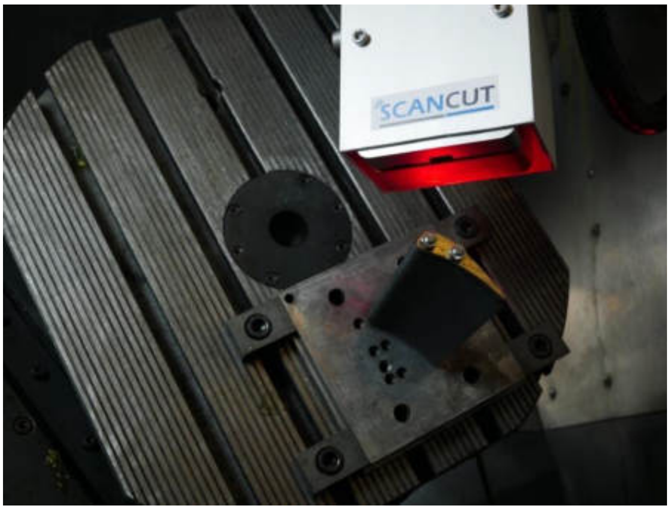
- Machining of CMCs and composite materials
- Ultrasonic-assisted milling and grinding
- 3D sensor technology, inline or offline
- Surface analysis
- Applied AI methods in machining

In the field of machining process optimization ultrasonic-assisted milling and grinding, as well as inline inspection using white light interferometer (WLI) are of particular interest to the department. Inline inspection in particular enables efficient quality assurance and adaptive machining.

HSA_comp, in partnership with industrial collaborators, is working on the SCANCUT project, which seeks to revolutionize the field of 3D inspection of CMC surfaces. The project is developing a new principle that enables "in situ" inspection during the finishing process. A key component of this approach involves integrating WLI technology into a machine tool for the first time. The ultimate objective is to achieve automatic defect detection, which can be correlated with process parameters to facilitate an adaptive process strategy that minimizes errors in machining. This approach also combines finishing and quality control into a single step, eliminating the need for re-clamping the workpiece during reworking. This result is significant time and cost savings, making the SCANCUT project a game-changer in the field of machining.



Component edge with automatically detected edge breakout @ HSA_comp



Component edge with automatically detected edge breakout @ HSA_comp

HSA_comp's research and development strategy emphasizes practical and application-oriented approaches that enable the team to effectively collaborate with industrial partners and carry out contract research projects. The Composite Process Technology department is well-suited for partnerships with medium-sized companies to implement their innovations due to its short communication and collaboration channels. The bachelor's, master's, and PhD theses on composite technologies offered by HSA_comp serve as a solid foundation for aspiring engineers looking to enter in-demand fields. Additionally, the innovative topics and research projects undertaken by HSA_comp increase the attractiveness of studying at the faculty. Overall, HSA_comp's focus on cutting-edge research and real-world solutions makes it an ideal partner for those seeking to benefit from the latest advances in composite process technology.

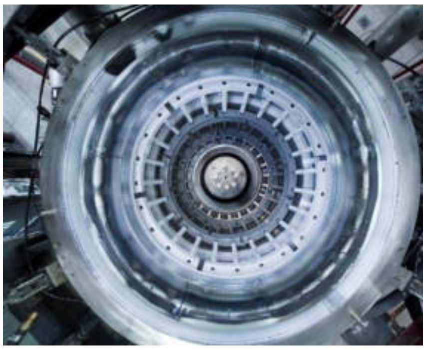
CVT GmbH & Co. KG: The CVT exists in its current form with about 50 employees since 2006. The motto is: "Gas to Solid", which is often implemented together with other partners. The field of activity of CVT is high-performance ceramics. Using its own patantized CVI process, CVT mainly produces C/C materials, primarily high-performance C/C materials for friction applications. The strength of CVT is the matching of the morphology of the matrix to its needs.

As the world's leading manufacturer of C/C friction materials produced by r-CVI and an expert in chemical vapor deposition (CVD) processes, CVT has the ideal technical prerequisites to successfully handle development tasks and experimental work.

In doing so, CVT relies on cooperation at eye level between manufacturers and customers on a technical scale.

C/C Materials @ CVT

CVI Reactor @ CVT



Inside of an CVD Reactor @ CVT

The DLR Institute of Material Research: at the German Aerospace Center (DLR) in Cologne conducts research on the development of new material solutions and processing technologies primarily for aeronautics, space, energy and transport applications. About 120 employees work across a wide range of materials and research topics including ceramics, metallic structures and hybrid materials, high temperature and functional coatings, aerogels and thermoelectric systems.

Antenna cover and turbine guide vane made of alumina CMC by infusion technology @ DLR-WF

Combustion chamber made of alumina CMC by winding technology @ DLR-WF

The DLR-WF department of Structural and Functional Ceramics has two main areas of research: i) fiber reinforced ceramic composites for aerospace and energy applications such as aircraft engines, gas turbines and thermal protection systems to enable increased performance and efficiency and ii) functional ceramic materials for sustainable solar thermal energy conversion and storage. With over 20 years of fundamental and applied R&D experience in the field of ceramic composites, DLR-WF has a very strong expertise in the development of ceramic materials, processes and advanced fabrication technologies, with a particular focus on oxide CMC. In addition, DLR-WF offers cutting-edge testing facilities for thermo-mechanical and microstructural characterization and non-destructive testing for the comprehensive characterisation and analysis of CMC and fibre materials from room temperature up to 1,500°C.

Current research activities include the optimization of high temperature properties of alumina and mullite-based CMC for highly demanding applications > 1, 000°C, the development of new lightweight, cost-efficient CMC for use temperatures < 1,000°C and the development of novel fabrication technologies towards the automatable and economical serial production of CMC components. The ceramic activities of DLR-WF are complemented by the design, simulation and component testing expertise of the department of Ceramic Composites and Structures at the DLR Institute for Structures and Design in Stuttgart. Together, both departments form the center of DLRs ceramic and CMC research activities and collaboratively work towards establishing a fully integrated physical and digital process chain from basic material and process development to design, simulation, manufacturing, quality control and product validation for both oxide and non-oxide CMC.

The DLR Institute of Strucutre and Design: The Institute of Structures and Design (BT) of the German Aerospace Center (DLR e.V.) has decades of expertise in the development of materials for efficient high-temperature lightweight design. Together with its 150 employees and the colleagues of the Institute of Materials Research (WF), new processes and design methods are continuously being developed for innovative high-performance structures in the fields of aerospace, vehicle construction and energy technology. The basis of these developments is the interaction of high-performance, temperature-resistant materials and innovative digital methods. The result: new technological developments for a sustainable future.

Together with the department of Structural and Functional Ceramics (WF-SFK), the Ceramic Composites and Structures department (BT-KVS) designs and creates both oxide and non-oxide materials, as well as processes for manufacturing lightweight ceramic matrix composites subject to high thermal and mechanical loads. The secret of success lies above all in the multidisciplinary cooperation between different development areas. Thus, component and material development are not only considered independently, but their structural integrity is also integrated into the engineering chain by means of process-optimized modeling tools.

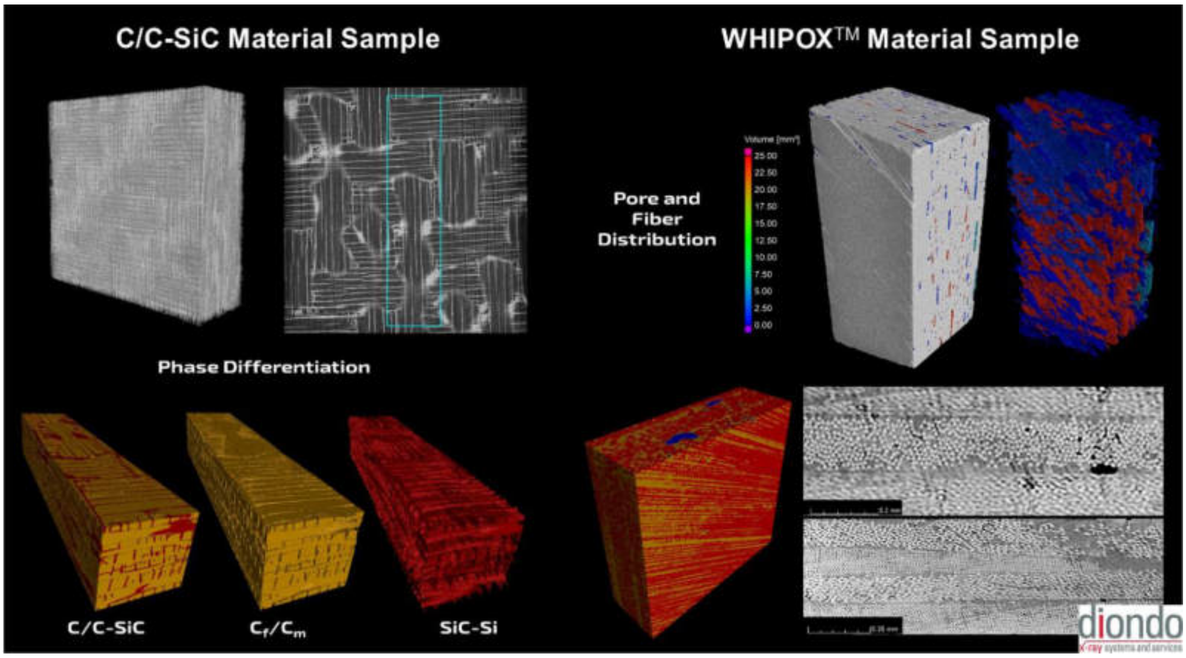
By digitally and analogously mapping the process chain from material development to prototype production and linking material characterization and non-destructive analysis, new developments can be produced quickly, cost-effectively and without rejects, even for complex component geometries.

For the fabrication of non-oxide fiber reinforced ceramics, mainly, within DLR, the Reactive Melt Infiltration (RMI) and Liquid Siliconization Infiltration (LSI) processes are used to produce CMCs with tailored material properties. These components can be used at temperatures ranging from room temperature to over 2000°C. In cooperation with other DLR institutes, developed structures are not only tested under relevant conditions, but also applied in real life. Be it as thermal protection systems on sounding rockets, as engine components in the aerospace industry or as ceramic brake discs for cars, airplanes and propellers. The use of different matrices, fiber materials and shaping methods such as hot pressing, autoclaving, RTM and winding processes is constantly expanding the range of applications with regard to the lifecycle and atmospheric conditions of the high-performance structures, so that new areas of application can be continuously opened up.

Here, the available infrastructure also makes the difference. Adapted CAD and FEM systems for the calculation of structures in the real application, as well as furnace systems for pyrolysis and silicification in different sizes and temperature ranges enable process-optimized component development. Modern testing facilities for quality assurance such as CT and air ultrasound systems, as well as scanning electron microscopy with connected energy dispersive X-ray spectroscopy guarantee development projects with the highest technology standards.



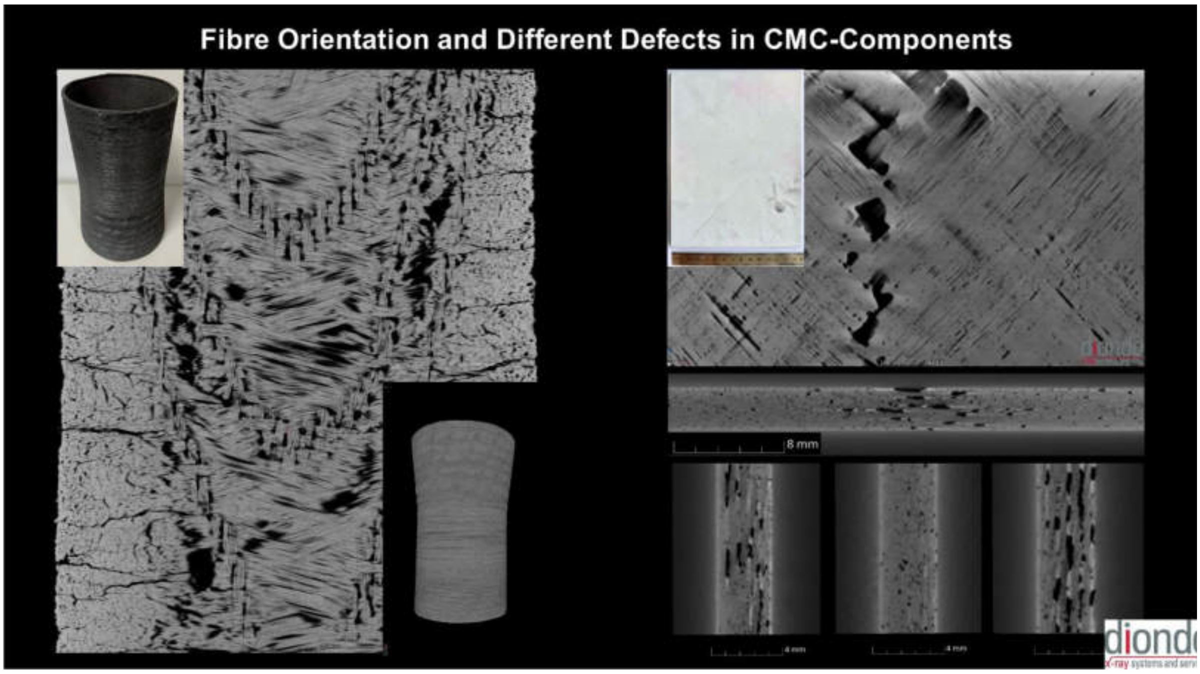

Diondo GmbH: is a leading manufacturer of innovative computed tomography (CT) systems in the field of non-destructive testing with more than 25 years' experience. Leading companies from automotive, aerospace and defence industries as well as world-class institutes are among our customers. In our in-house application laboratory that is equipped with a powerful setup of different CT systems that is unique in Germany, we provide CT scanning services as well. Our CT service customers benefit from a broad variety of CT scanners from highest-resolution micro-CT for detailed materials characterization up to a 6 MeV high-energy CT system for examining larger and highly absorbent components. The successful use of ceramic composites requires a detailed understanding of the internal structure of different materials, their behaviour and damage evolution under load, as well as possible deviations of manufactured parts from the originally conceived design. In all these cases, the non-destructive examinations with our CT systems provide valuable insights for the further development of CMC components towards their readiness for series production.



High-resolution micro-CT investigations for material characterization @ diondo

Micro-CT scans on CMC material samples with spatial resolutions at micrometre range allow us to contrast the internal material structure in three dimensions, which provides our customers with valuable information in the development of their materials. Based on the CT results, we can, for example, differentiate the different phases in the material and determine the proportion and orientation of the fibres in the matrix. By superimposing a mechanical tensile or compressive load on the sample during CT testing (so called In-Situ CT, F_{max} < 10 kN), we gain a better understanding of the effects of mechanical stresses on the complex material e.g. by the determination of displacement and strain fields using digital volume correlation methods. Furthermore, we gain relevant information on fibre-matrix bonding as well as crack initiation in the material. On larger CMC components, such as plates and pipes from the chemical industry or combustion technology as well as components planned for usage in aerospace engines, the CT examinations provide information on the quality of the manufacturing process.

Different features and defects such as porosity and pore distribution, delaminations and cracks are detected reliably and non-destructively and their exact position in the component is localised. Based on the CT results, measurements of the component geometry can also be carried out up to a variance comparison of the manufactured component to its CAD design. CT-based determination of the fibre orientation in the component and calculation of orientation tensors provide valuable "as-built" information that can be retroactively incorporated into virtual CMC design processes, for example. To drive the further commercialisation of CMC materials, diondo participates in public R&D projects and continues to develop CT technology in this context in order to be able to reliably detect smaller features in larger CMC components. In addition, we are actively involved in various networks and associations that deal with issues relating to the production of fibre-reinforced composites suitable for series production.



CT investigations to determine fibre orientation and defects in components @ diondo

Fraunhofer IGCV stands for application-oriented research with a focus on engineering, production and multi-material solutions. The focus is on integrated innovations at the level of manufacturing processes and material sciences, machines and process chains, as well as factory and company networks. This enables multidisciplinary solutions from materials engineering and component design to production engineering and the supply chain.

With about 160 employees at locations in Augsburg and Munich, we support our partners as part of the Fraunhofer Group "Production" in the form of short-, medium- and long-term research projects. By transferring basic knowledge into customer-specific solutions and using state-of-the-art infrastructure, we accelerate the transfer of knowledge to ensure the sustainable competitiveness of our partners in the long term.

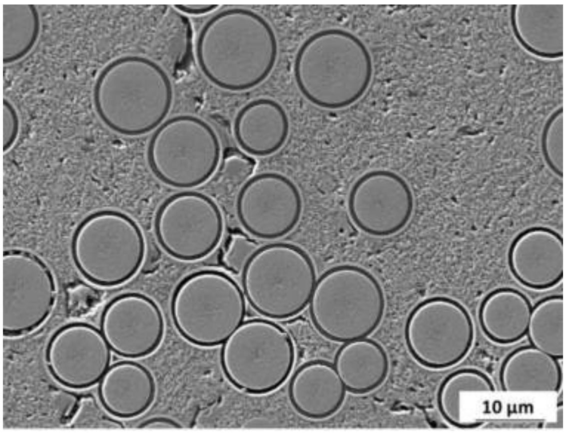
Ceramic composite materials are also used in various contexts to solve research tasks. A unique selling point in this area is the existing process technologies, which are used as pilot plants on an industrial scale for development. Fiber materials of any fiber length, from staple fibers to continuous filaments, can be processed into high-performance semi-finished products and composites along modern process chains, including nonwovens technology, fiber patch placement (FPP), pultrusion, as well as automated tape laying (ATL) and automated fiber placement (AFP).

Fraunhofer IKTS: Fraunhofer IKTS develops CMC for use in combustion chambers of gas turbines, mechanical engineering and plants of the chemical industry. SiC/SiC is predestined for application temperatures above 1100 °C, especially when high strength and creep resistance are required due to mechanical stress.

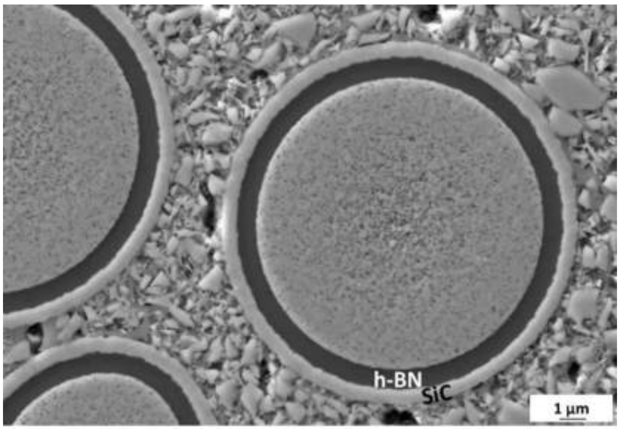
With the equipment available at IKTS, oxide and non-oxide CMC with tailored properties can be produced, starting with the coating of the fibers via CVD, the shaping and densification of the matrix with slurry/PIP/LSI up to the application of corrosion protection coatings (EBC), e.g. via liquid phase coating (slurry) and laser sealing. Important mechanical parameters up to 1,600 °C can be determined for component design. CMC and corrosion protection coatings (EBC) with improved long-term stability are developed on the basis of hot gas tests in a flowing fuel gas atmosphere under defined water vapor partial pressure. These dense materials are not damage tolerant without fiber coating. Fiber coatings are being developed using the CVD process to ensure the required crack deflection in the material and to protect the SiC fibers from oxidation. Coatings based on PyC and h-BN are state of the art. Current research is focused on the deposition of double layers, e.g. with SiC top layer in a continuous coating process.

Our Offer:

- Coating of SiC fibers (CVD), layer development and characterization.
- Production and development of CMC with adapted properties,
- Mechanical characterization up to 1,600 °C,
- Oxidation tests, investigation of stability against hot gas corrosion (950 °C-1,450 °C, 50-100 m/s),
- Development of anti-corrosion coatings (EBC)



SiC/SiC produced via PIP process: SiC fibers in dense SiC(N) matrix @ FhG IKTS



SiC/SiC produced via PIP process: BN+SiC double layer on SiC fibers @ FhG IKTS

Fraunhofer ISC/HTL: The Fraunhofer Center HTL bundles the ceramics activities of the Fraunhofer Institute for Silicate Research ISC. It currently has around 100 employees at its three locations in Bayreuth, Würzburg and Münchberg. More than 4700 m2 of high-quality laboratory and pilot plant facilities with state-of-the-art equipment are available for development projects and R&D services.

At the Fraunhofer Centre HTL, composites are developed in a closed process chain from component design and material design to production on a pilot plant scale and testing of the application behaviour. The technological focus is on the production of lightweight components made of ceramic matrix composites (CMC). The entire process chain is covered, starting with the development of ceramic fibers and their coating, through textile fiber processing, matrix construction, thermal processing and joining, to final processing. In addition, processes such as additive manufacturing are available for the production of metal and ceramic components with complex geometries.

For the production of fiber composite components, pilot plants are available which allow laboratory samples to be scaled up to large component dimensions of up to approx. 1000 mm. For the up-scaling of newly developed ceramic fibers, a fiber pilot plant is available which allows production on a tonne scale. For green production, hot presses, a CNC-controlled 5 axes winding unit, a robot-system, a continuously operating prepreg unit for impregnation of fiber preforms and a computer controlled 2D cutter for prepregs and fabrics are ready for use. Further plants for textile fiber processing are located at the Centre for Textile Fiber Ceramics TFK at the Münchberg site.

Partial segment of a mixer made of GMC (geopolymer matrix composite) with basalt fibers @ HTL

Partial segment of an OFC mixer made from silica fibers and oxide ceramic matrix @ HTL

Laval nozzle of C/SiC (LSI) @ HTL

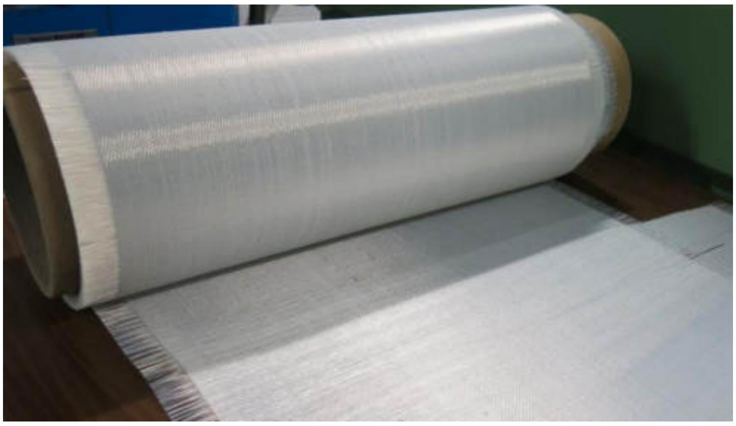
The parameters of heat treatment processes are optimised for manufacturers of ceramic and metal components. New materials are developed together with manufacturers of high-temperature materials: Ceramics and powder metals and refractory materials. High-temperature components are designed and built as prototypes for manufacturers of thermal process technology and their application behaviour is tested.

To test high-temperature materials and optimise their manufacturing processes, the Fraunhofer Centre HTL develops so-called thermo-optical measuring furnaces (TOM). Materials and components can also be characterised using various non-destructive and mechanical testing methods as well as thermal testing methods.

The German Institutes of Textile and Fiber Research in Denkendorf are Europe's largest textile research center. At the research center, a wide variety of issues along the entire fiber and textile manufacturing chain can be addressed using state-of-the-art technologies on an area of more than 25,000 m2. For a long time now, the focus has not only been on apparel textiles, but to a large extent on technical applications of fiber-based textile structures. This means that nowadays applied research and development, like the one carried out in Denkendorf, forms the basis for various enabling technologies in which fibers and textiles play a decisive role.

For more than 30 years, continuous research has been conducted at the DITF on the development of oxide ceramic fibers, which are the crucial component in fiber-reinforced ceramics, so-called CMC.

Burner nozzle made of OxCeFi fibers @ DITF

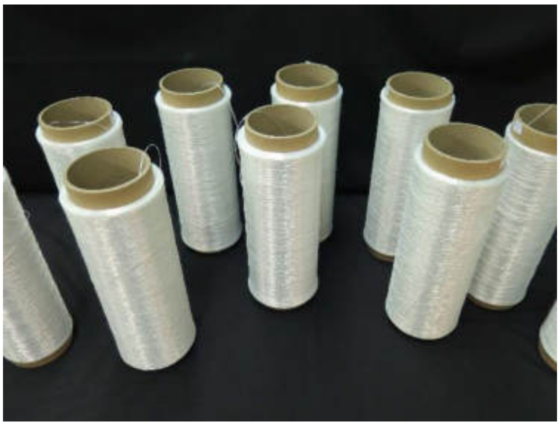


Woven fabric made from OxCeFi A99 fibers @ DITF

In terms of developments and technological status in the field of oxide ceramic fibers, the DITF occupies a leading position worldwide and these activities constitute a unique feature in the landscape of textile research institutions in Europe.

Research activities focus on the production of alumina- and mullite-based high-performance ceramic fibers, with the emphasis on material development on the one hand and the development of a manufacturing process suitable for industrial use on the other.

The OxCeFi fibers developed in Denkendorf already achieve the properties of the best commercially available oxide fibers. The research strategy aims to develop ceramic fibers based on new compositions and with improved and extended property profiles in order to pass this know-how on to industrial partners. In the meantime, there is close cooperation with an industrial company that would like to produce the DITF fibers commercially.



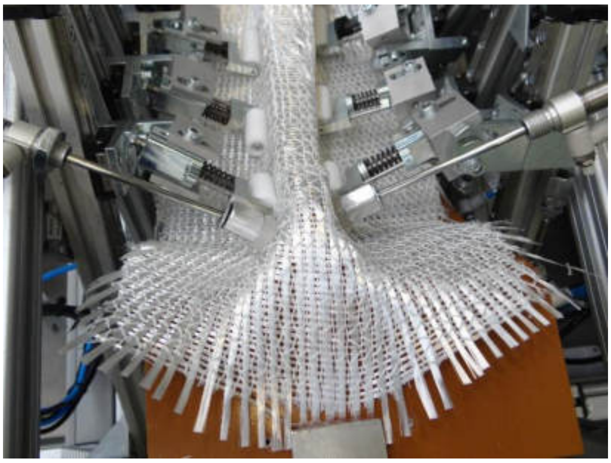
OxCeFi A99 Aluminium Oxide Fibers @ DITF

OxCeFi fiber weaving, @ DITF

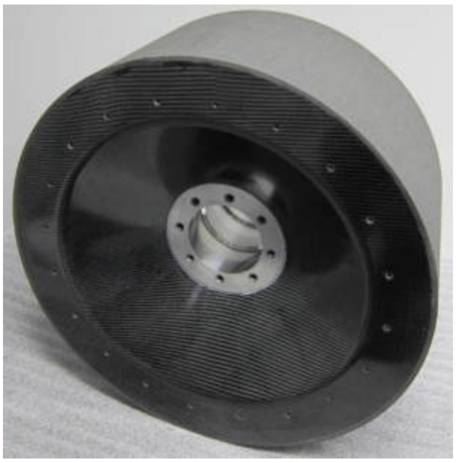
Gustav Gerster GmbH & Co. KG: The Gerster TechTex business unit of Gustav Gerster GmbH & Co. KG supports efforts in automation, in the reduction of handling effort and in the reduction of waste with textile innovations around textile preforms and highly drapable wide fabrics.

One example of textile preforms is woven spiral tapes in round components. Round spiral tapes are designed completely to fit the component and can be found in mechanical engineering and ceramic brakes, among other applications. The fiber structure can be varied according to the load from purely unidirectional (in circumferential direction), purely radial to different warp and weft densities.

Complex geometries can usually only be realized by cutting textile webs. The reason for this are limitations in the drapability of textiles. This is due to the fixation of the fibers to each other, in the case of fabrics by sewing threads, in the case of woven fabrics by friction of the fibers in the weave structure, as well as the inherent stiffness of the fibers. The highly drapable DRAPFIX and DRAPTEX biaxial fabrics from Gustav Gerster allow the fibers to be displaced in their longitudinal direction, with the fiber spacing remaining virtually unchanged. The draping process itself is carried out by stretching out the textile. With longer travel, yarns are drawn in from the edge; with shorter travel, fibers are pushed out over the cut edge. Spreading processes can be easily automated, among other things via movable rollers, flexible mats or adapted pressing tools. In addition to improved drapeability and "matching" fiber lengths, only low restoring forces result from the inherent stiffness of the fibers themselves. The forming geometry of the textile in the mold is thus much better preserved. It is also possible to vary different fibers, such as carbon and aluminum oxide fibers, within the scrim. The high drapeability, the low restoring forces and the use of locally adapted fiber types contribute to the load-oriented production of complex geometries in a single step, which is particularly beneficial for processes with short cycle times.



DRAPFIX biaxial fabrics, example of a forming geometry @ Gerster



Continuous spiral belt / CFRP base body for CBN grinding wheels @ Gerster

Gühring KG was founded in 1898 and today, with 8000 employees, is one of the leading manufacturers of rotationally symmetrical cutting tools such as drills, reamers, threading tools, end mills and special tools. The carbide for these high-quality cutting tools is produced and coated in-house. But also high-speed steel, CBN and PCD are used as cutting materials. In research and development, more than 100 employees work on new ways to mechanically machine modern materials, special alloys and special materials from a wide range of industries. Since 2012, for example, Gühring has also been conducting intensive basic research into the machining of fiber-reinforced CMC materials, together with various partners and institutes from the Ceramic Composites Network. After new cutting materials and cutting tools have already been developed in the basic research, the focus of the investigations is now on the entire cutting process with an adapted cooling strategy. In addition, Gühring is active in various pre-competitive research projects with the aim of optimizing the entire process chain of additively manufactured CMC.

5-axis machining turbine blade @ Gühring

Basic investigation of chicane component @ Gühring

The Institute for Materials Science at Hof University of Applied Sciences (ifm) is involved in the development of textile semi-finished products for the manufacture of highly specialized CMC components. In particular, circular needling technology offers the possibilities for developing multilayer, radially reinforced tubular structures from any combination of starting materials. Based on the relevant know-how, which has been acquired in the course of successfully completed research projects related to flat needling technology, Hof University of Applied Sciences occupies a special position with regard to the development of z-reinforced, textile semi-finished products. The ifm offers potential project partners the chance to distinguish themselves clearly from the state of the art by CMC tube structures with significantly improved mechanical and thermal properties.

In addition to load-oriented special solutions, the Hof University of Applied Sciences is able to produce almost all variants of textile sheet structures from inorganic fibers and to further develop them in a customer-oriented manner due to its modern and diverse machinery. The Institute of Materials Science at Hof University of Applied Sciences sees itself as a highly committed companion for end users from the aerospace and automotive industries. From the precise selection of fibers to textile production and continuous validation of the development progress, through a broad and well-founded range of tests, to support with questions about various infiltration techniques, the Hof University of Applied Sciences stands by its partners with highly specialized personnel in the sense of joint value creation.

IBT Thermoprocess GmbH specializes in the production of high-temperature furnaces for debinding and sintering of ceramics. Other processes such as CVD processes and pyrolysis can also be realized. IBG GmbH offers heating and sintering systems with microwave heating for ceramics with very low thermal conductivity, which are significantly more difficult to debind and sinter than ceramics with high thermal conductivity. Microwaves, known from the household, penetrate into the workpiece and are only converted into heat in the body. Under the influence of microwave radiation and its distribution, the energy input changes over the component and enables a high temperature uniformity.

Microwave unit of the ThermoLine-HEAT series @ IBT

Vacuum furnace of the ThermoLine-VAC series @ IBT

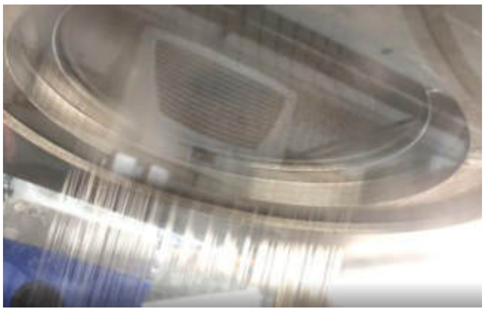
The figure below shows such a system with a drying or debinding tray as well as a sintering tray. How can ceramics be sintered under temperatures of 3000 °C? IBT's high-temperature furnaces can handle this demanding task. A water-cooled vessel, which can be evacuated to 1*10-6 mbar, hides a lot of thermal insulation made of graphite fibers inside, as well as a heating element made of carbon fiber reinforced carbon (CFC). Since at these temperatures, even under vacuum, the carbon oxidizes with the few remaining oxygen compounds, the container is purged with inert gas (e.g. argon) after evacuation. In this way, the concentration of oxygen is lowered again, and the carbon is deprived of its reaction partner. As a result, the heater can reach temperatures of up to 3000 °C, usually under low voltage.

In today's world, reducing energy consumption is a key issue for cost and climate reasons. Here IBT, in cooperation with research institutes, is developing new types of thermal insulation - including CMC materials, to reduce heat losses and thus energy consumption. With the heating elements made of CFC (carbon fiber reinforced carbon), a CMC material is also used as a heating source. This closes the circle.

<u>OxiCer: OFC for large-scale production:</u> The network "Development of an innovative large-scale production technology for fiber-reinforced oxide ceramic composites" (OxiCer) was launched in January 2020. OxiCer pursues the goal of researching ceramic components for high-temperature applications. The network is a sub network of the Ceramic Composites and is composed of three research institutions, 13 small and medium-sized enterprises and five associated network partners. The network is coordinated by scientists from the Chair of Structural Lightweight Design and Plastics Processing (SLK) at Chemnitz University of Technology. The common goal of the network is to develop processes, services, and products from research to marketing in the field of fiber-reinforced oxide ceramics. Wherever high temperatures occur, and metal alloys reach their limits in corrosive environments, fiber-reinforced oxide ceramic components are in demand. They can withstand temperatures of over 1,000 °C and, thanks to their fiber reinforcement, can compensate for rapid temperature changes without functional impairment. The aim is to develop new, efficient, and resource-saving manufacturing technologies with which high volumes can be produced with short cycle times.

RATH GmbH New European supplier for continuous oxide-ceramic fibers: For more than 130 years RATH has been burning for refractory products: This makes the Austrian company, which operates internationally, one of the most recognized specialists in the field of refractory technology. Based on more than three decades of experience in the development and manufacturing of high-temperature ceramic fibers, Rath is on its way to becoming the first European supplier of continuous oxide-ceramic fibers in Europe.

The specialists at RATH have extensive know-how of the aluminum, glass, iron and steel, energy, chemical or ceramics industry, which enables them to understand the specific requirements and processes of each customer. Furthermore, the company attaches high importance to research and development: Based on 35 years of experience in the development and manufacturing of high-temperature ceramic fibers, RATH continues to search for innovative ways to provide new product solutions for the industry. Continuously spun oxide-ceramic fibers represent a critical raw material for the manufacturing of oxide-ceramic matrix composites. These types of fibers prove to be one of the most innovative and most challenging materials to manufacture in the ceramic sector. There is only one relevant supplier in the entire world, which is located in the USA. Since oxide-ceramic fibers are labelled as dual-use goods, they are subject to export control and hence the supply of fibers to Europe is uncertain and slow. Acknowledging that there is a strong request for a European supplier for these fibers, RATH took up the challenge and continues to develop product solutions for Ox-CMC manufacturers. Thus, the company is on its way to becoming the first European supplier for oxide-ceramic fibers and looking forward to providing state-of-the-art oxide-ceramic fibers with the highest quality in mechanical strength and thermal stability.



Spinning nozzle @ Rath

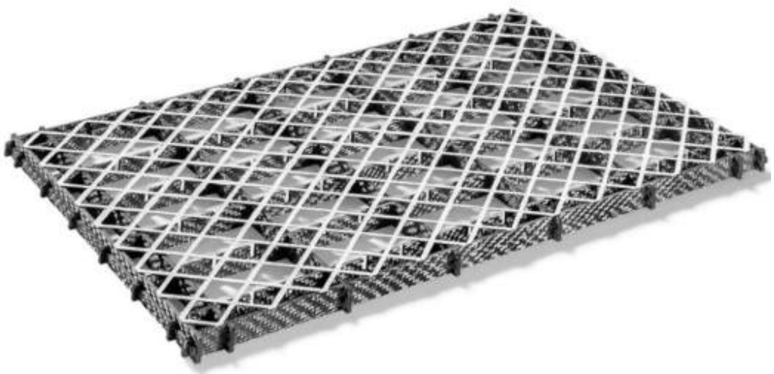
Oxide Fiber @ Rath

Oxide Fiber @ Rath

Schunk Kohlenstofftechnik GmbH - Experienced development partner for high temperature applications: Schunk is a global leader in the development, production and application of carbon and ceramic solutions. Schunk combines innovative strength and technological know-how with exceptional service orientation to provide a range of services that is unique in the market. In doing so, Schunk combines innovations - such as patented components for the maintenance of heating chambers, silicified material solutions or intelligent designs for batch carriers - with comprehensive expertise in all aspects of materials and applications. The result is solutions which combine economy, energy efficiency and durability in a successful way.
The customers benefit from graphite and CFC materials which remain dimensionally stable even well above the melting temperature of most metals and exhibit only low thermal distortion and excellent thermal shock resistance.

From heat treatment to semiconductor industry: One can rely on ceramic fiber composites from Schunk in virtually all high-temperature applications: In the heat treatment, semiconductor and solar industries, as well as in the processing of aluminum.

Heater components
@ Schunk



Hybrid Batch Carrier @ Schunk

In heat treatment, the customers rely on the advantages of furnace components, insulation materials, carrier systems, kiln furniture and solutions for temperature measurement. For the semiconductor and solar industries, Schunk offers customized solutions for polysilicon recovery, CZ pullers, DSS hot zone, and C/C carriers for PECVD systems.

For the particularly demanding environment in the processing of aluminum Schunk has developed Durafox® Ceramics. Equipment parts and auxiliary materials made of this material have a high damage tolerance as well as thermal shock resistance and can be used for temperatures of up to 1,100 °C.

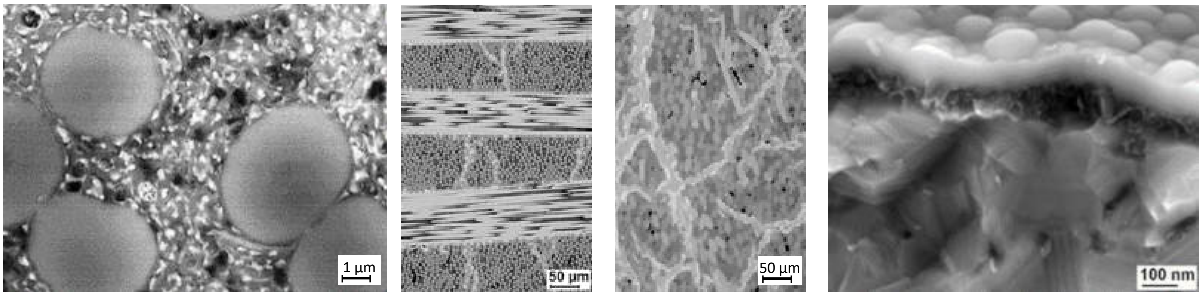
SGL Carbon GmbH: SGL Carbon is a technology-based company and world leader in the development and production of carbon-based solutions. Its high-quality materials and products made from specialty graphite and composites are used in industrial sectors that determine the future: automotive, aerospace, solar and wind energy, semiconductor and LEDs as well as in the production of lithium-ion batteries, fuel cell and other energy storage systems. In addition, SGL Carbon develops solutions for chemical and industrial applications. Further developments in these areas demand more intelligent, more efficient, networked and sustainable solutions. This is where the entrepreneurial vision of SGL Carbon evolves around: contributing to a smarter world. In 2021, SGL Carbon SE generated sales of around 1.0 billion euros. The company has approx. 4,700 employees at 31 locations in Europe, North America, and Asia.

TU Chemnitz – Group of Composites and Material Compounds (TUC-PVW): The CMC working group of the Group of Composites and Material Compounds has been conducting research in the field of carbon fiber-reinforced carbon composites (C/C) with subsequent siliconisation (C/C-SiC) for many years. These materials have excellent chemical, thermal and mechanical properties. A major focus is microstructure-correlated research into different manufacturing methods and process variations in the CFRP, C/C and C/C-SiC states. The working group is specifically concerned with:

- the research and development of adapted carbon precursors about porosity and processability,
- the LPI process (Liquid Polymer Infiltration) for the development of high-temperature resistant C/C-SiC or C/C-SiCN composites,
- the LSI process (Liquid Silicon Infiltration) or field-assisted silicification (FAST-LSI) to provide high-temperature-resistant C/C-SiC composites,
- the large-scale production of C/C-SiC composites by injection moulding as a shaping step,

- fiber/matrix interface adaptation by CVD coating,
- the further processing of CMC into hybrid components,
- the joining of CMC and finally
- the characterisation of CMC (e.g., microstructure, phase analysis by Raman microscopy, damping, mechanical testing in the SEM).

Scanning electron microscope images of C/C-SiC composites and fiber coatings that are being researched at the Group of Composites and Material Compounds.



C/C-SiC dual matrix composites @ TUC-PVW

C/C-SiC-Composites hand-laminated @ TUC-PVW

C/C-SiC-Composites injection moulded @ TUC-PVW

BNx/SiNx-Coating (CVD), SiC-Fiber @ TUC-PVW

Another research focus is the coating of multifilament fibers by means of chemical vapour deposition (CVD). With this process it is possible to deposit uniform and homogeneous layers of Y_2O_3, BN and SiN as well as combinations thereof onto SiC multifilaments down to the core of a fiber bundle. In addition to discontinuous coating experiments for basic research, the CVD system technology is currently being expanded for continuous coating of the fiber bundles to enable textile processing of the fibers.

TU Chemnitz, Endowed Research Group "Textile Plastic Composites and Hybrid Compounds": The TKV, which is associated with the Chair of Lightweight Structures and Polymer Technology (SLK) at Chemnitz University of Technology, has already been conducting research in the field of CMC for many years. In particular, the focus is on shaping processes suitable for large-scale production, which enable the fully automated, energy-efficient and resource-saving manufacture of complexly designed components.

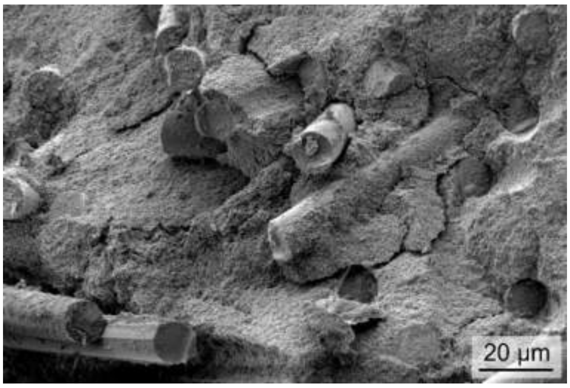
In the case of non-oxide fiber-reinforced ceramics, the thermoset injection molding process is used to process compounds containing carbon fibers and phenolic resins. By means of the liquid silicon infiltration (LSI) process, a carbon fiber reinforced ceramic based on silicon carbide (C/C-SiC) is formed as the final product (figure below, left). Development topics are currently

- various measures to increase the fiber length,
- the integration of inliners (textile semi-finished product or lost core) and
- the performance of sustainability analyses.

For oxide CMC, the ceramic injection molding and the extrusion printing process are being adapted for manufacturing (figure below, right). Fiber-reinforced feedstocks are developed that are suitable for the molding. Further processing is performed by debinding and sintering. The focus of current research is on

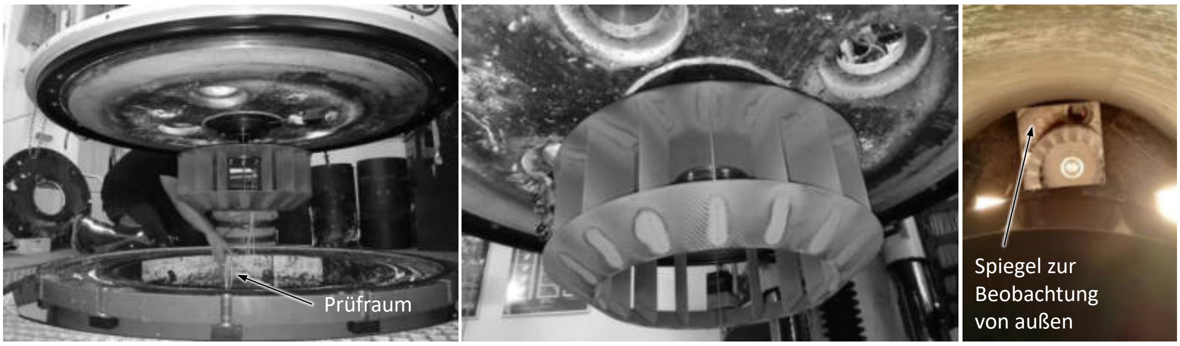
- the optimization of fiber-reinforced feedstocks,
- the integration of textile inliners and
- the adaptation of debinding and sintering parameters.

C/C-SiC brake discs for GoCarts via injection moulding and LSI @ TUC-TKV

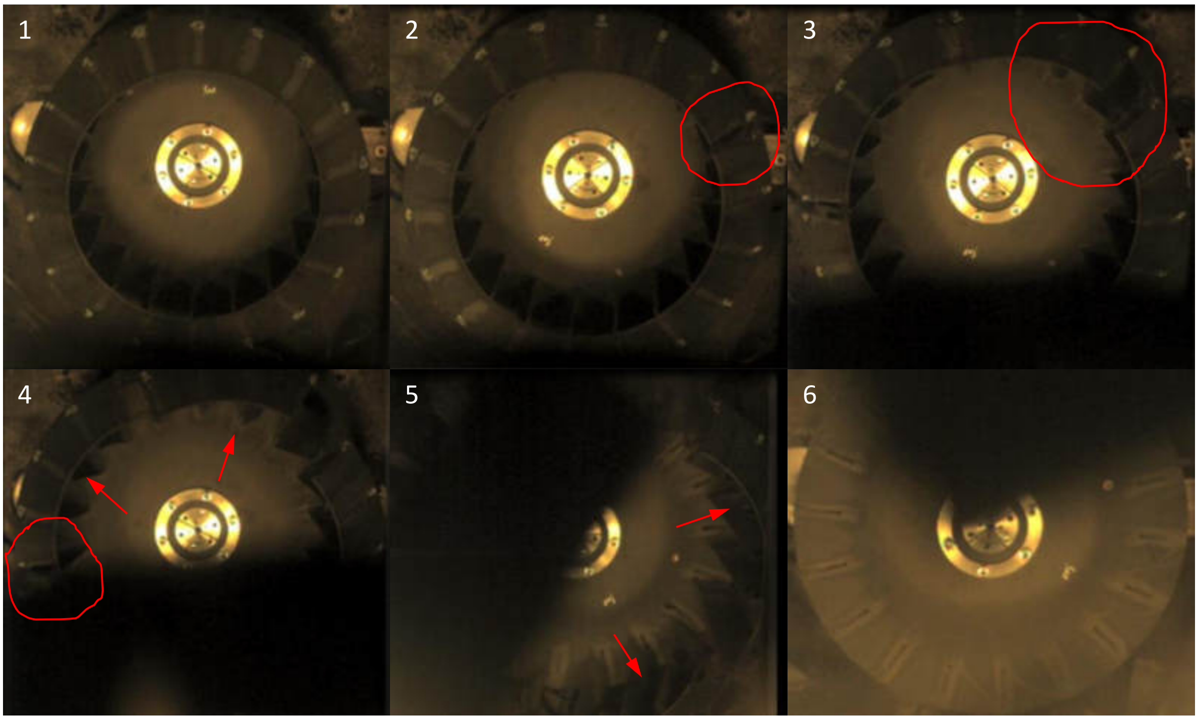


Fracture surface of a short fiber reinforced OFC @ TUC-TKV

At the Institute of Lightweight Engineering and Polymer Technology (TUD-ILK) at the TU Dresden, extensive R&D work is being carried out in the field of load-adapted lightweight structures. This is based on a cross-material and cross-product approach that covers the entire development chain - materials, design, simulation, production, prototype, quality assurance and costs. On the basis of fundamental research projects, the ILK has a large amount of experience in the development of material and process models, component and process design as well



Test set-up for the burst test of a C/C fan wheel (Schunk Kohlenstofftechnik GmbH) with more than double the nominal speed @ ILK



High-speed images (1-6) for verification of the numerically calculated structural failure of a C/C fan wheel (Schunk Kohlenstofftechnik GmbH) @ILK

as recycling and circular economy, especially of hybrid and multimaterial lightweight structures. A long-standing expertise is the deformation and failure analysis for the design of textile-composite ceramic structures, especially for high-temperature resistant rotor applications. Within the framework of basic and applied research projects, activities include the design and dimensioning of ultrafast rotating anodes made of carbon fibre-reinforced carbons (C/C) for high-performance X-ray tubes, the development of new damage and failure models for Ox/Ox ceramics for use in modern aircraft jet engines, and the design and testing of high-temperature-stable C/C fan wheels (figure below) for energy savings in industrial thermal processes. By comparing simulation and experiment, the developed material models are validated by means of real-time deformation measurement. In addition, the analytically or numerically calculated structural failure is verified in component tests, as shown in figure below, using high-speed camera technology, for example in the ILK rotor test rigs.

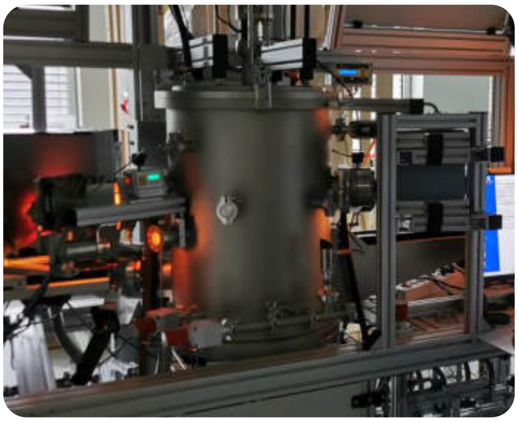
University of Augsburg, Institute for Material Ressource Management: The chair "Materials Engineering" was newly founded in 2019 by Prof. Dr.-Ing. Dietmar Koch at the Institute for Materials Resource Management at the University of Augsburg. It is dedicated to sustainable, digitally supported materials development and takes a holistic view of the structural and functional materials produced in the circular economy system: from production and the use phase to repair and recycling.

The central focus of the research at the chair is the reproducible and precisely defined controlled production of CMC. This includes the entire process chain, from production to recycling. Material synthesis, energy- and resource-efficient ceramic process technology, preform technology, shaping, property testing and life cycle assessment are important sub-aspects. The expertise at the chair is in developing customised materials for specific applications. Composites and hybrid structures with desired fiber architecture, hierarchical structure and adjusted pore morphology are produced on different scales. From the application scenario of a target component, the right material composition and combination are defined and then the component production is implemented technologically.

Important aspects are the ceramic process technology and the material science analysis of the ceramic materials, with a focus on the investigation of the fiber-matrix interface as a function of the manufacturing process and the application conditions. Digital material development with predictable material properties is made possible through digital imaging of the material and correlation with its starting materials.

The entire process chain is controlled and measured using sensors so that all process data are available digitally. Furthermore, physical and mechanical material data are recorded and subsequently evaluated using sophisticated measurement techniques such as push-out, 3D strain measurement, computer tomography and acoustic emission analysis. This makes it possible to generate process-structure-property relationships of customised as well as cycle-oriented heterogeneous materials. The lightweight design potential is developed by means of optimal design and multi-material design (saving resources). At the same time, material cycles are implemented (reusing resources) and process chains for ceramic components are evaluated from raw material to end of life (analysing life cycles).

Fracture surface of a tough CMC @ DLR-BT



Diagnostic furnace for real and digital material development @ MRM

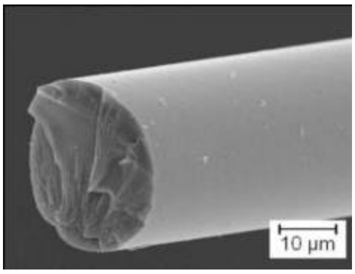
University of Bayreuth, Chair Ceramic Materials Engineering: The Chair focuses on education and basic research of functional and structural ceramic materials and has approximately thirty years of experience in synthesis, process and material developments and characterization of CMCs and polymer derived ceramics (PDC). Three research groups with about 30 scientists and technicians are supported by about 20 students. Investigated topics cover PDC-derived fibers and coatings as well as non-oxide (C/C-SiC, SiC/SiC) and oxide CMCs. Engineering aspects of CMCs from processing to prototype manufacturing and testing as well as the transfer of research results with industrial partners are a second focus of research activities.

Manufacturing and processing methods available include for example:

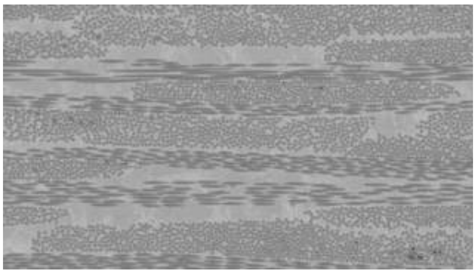
- Fiber production, coating, and thermal treatment

- Preform technology like fiber spinning, robot assisted short fiberspraying, winding, additive manufacturing and laminate technology
- Slurry based technology
- PIP/LPI
- Sintering
- LSI/RMI

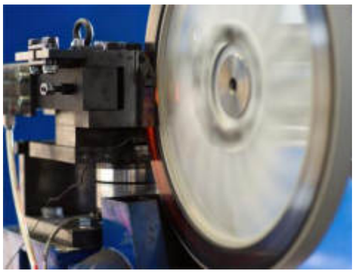
The fibers, coatings, hybrid materials and CMC components with possible prototype dimensions of up to 40 cm diameter are tested, modelled and evaluated with extensive characterization facilities. These facilities also include the capabilities to assess raw materials, simulate process steps, determine process and material parameters and finally to analyze the thermo-mechanical and application-oriented properties of the components. Hence, analysis methods and devices cover spectroscopy (FTIR, Raman, MS), TG-DSC, rheometry, particle analysis (size, shape, Zeta potential), dilatometry, SEM with EDX and EBSD, mechanical testing with loads up to 50 kN at room temperature and up to 1550 °C, tribological characterization from small scale tribometer up to full scale brake test rig as well as wetting behavior, layer adhesion, surface analysis and non-destructive testing methods (IET).



SiCN-Monofilament @ CME



Microstructure of oxide composite ceramic with Al2O3 fiber reinforcement @ CME



Brake test bench in cooperation with the Chair of CAD @ CME

Walter E. C. Pritzkow Spezialkeramik was founded in 1994 from the Pritzkow engineering office, which had been in existence since 1990. The focus of the company's work is on the development and design of lightweight ceramic structures that are used in the high-temperature range under extreme conditions. In 1995, company founder Walter Pritzkow received the Techtextil Innovation Award from the International Techtextile Committee for the development of oxide ceramic fiber composites with the brand name "Keramikblech". Since then, complex components made of "Keramikblech" have been developed and manufactured according to customer requirements.

WPX Faserkeramik GmbH develops, manufactures, and markets customer spedific ox/ox systems and components. WPX is a spin off from DLR German Aerospace Center, has been established in 2007, is located in Troisdorf and has become a leading European manufacturer of high-end ox/ox heat treatment solutions mainly to the automotive supplier industry. It cooperates closely with high end furnace and furnace equipment suppliers. WPX holds numerous ox/ox patents and is exclusive licensee of WHIPOX® technology from DLR. WPX components are used in vacuum, inert, induction and atmospheric furnaces, enabling high performance heat treatment processes at temperatures beyond 1.100°C, with high mechanical load, and under extreme thermal stress, like rapid gas quenching down to sub zero temperatures. WPX solutions allow energy efficient heat treatment, improve process and product quality, thereby supporting sustainable industrial processes.

Small Whipox Ox/Ox Batch Carrier and other Trays @ WPX

Large Whipox Ox/Ox Batch Carrier @ WPX

Others:

3D ICOM Technologies	Germany	SME
Airbus Defense & Space	Germany	LE
ArianeGroup	Germany	LE
ASGLAFORM composites GmbH	Germany	SME
Audi AG	Germany	LE
Automation Steeg und Hoffmeyer GmbH	Germany	SME
Automation W+R GmbH	Germany	SME
BCT Steuerungs- und DV-Systeme GmbH	Germany	SME
BJS Ceramics GmbH	Germany	SME
Brembo SGL Carbon Ceramic Brakes GmbH	Germany	LE
C6 Composite Tooling GmbH	Germany	SME
ConSus - ANT Stationary Cutting Solutions GmbH	Germany	SME
Deutsches Zentrum für Luft- und Raumfahrt BT	Germany	R&D
Deutsches Zentrum für Luft- und Raumfahrt SG	Germany	R&D
EiMa Mitte Vertriebs- und Service GmbH	Germany	SME
Evonik Industries AG	Germany	LE
FCT Anlagenbau GmbH	Germany	SME
FISCO GmbH	Germany	SME
Forschungszentrum Jülich	Germany	R&D
Fraunhofer EZRT	Germany	R&D
Fraunhofer IAP, PYCO	Germany	R&D

Fraunhofer IWM	Germany	R&D
Fraunhofer IZFP	Germany	R&D
Grasse Zur	Germany	SME
Hochschule Aalen	Germany	R&D
Hufschmied Zerspanungssysteme GmbH	Germany	SME
INVENT Innovative Verbundwerkstoffe	Germany	SME
Lebmeier Forschun Beratung Konstruktion	Germany	SME
Mayr Antriebstechnik – Chr. Mayr GmbH & Co. KG	Germany	SME
Modellbau Arnold GmbH & Co. KG	Germany	SME
MT Aerospace AG	Germany	LE
MTU Aero Engines AG	Germany	LE
nextGen Engineering GmbH	Austria	R&D
Premium Aerotec GmbH	Germany	LE
Röder Präzision GmbH	Germany	LE
Roth Composite Machinery GmbH	Germany	SME
Soffico	Germany	SME
Solidian GmbH	Germany	SME
Solvay - CYTEC Engineered Materials GmbH	Germany	LE
SUPSI, Institute of Mechanical Engineering and Materials Technology (MEMTi)	Switzerland	R&D
Technischen Universität München, Lehrstuhl für Carbon Composites (LCC)	Germany	R&D
Tenowo Hof GmbH	Germany	LE

2.2 Players within Europe

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

2.3 Players USA (+ Canada)

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

2.4 Players in Asia and Australia

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

3 Main applications

Not all imaginable applications from CMC are described here. The aim of the market report is to generate a comprehensible overview of tonnages and sales in chapter 4. For this purpose, it is helpful to briefly describe the main sales markets of CMC. There are many stand-alone solutions or prototypes from CMC, which are explicitly not described here.

3.1 Automotive

Two different types of CMC are used commercially in the automotive sector today: CMC brakes for sports cars in street use and CMC brakes for motorsport. Both systems differ technologically, and both systems will be briefly described here.

Vehicle brakes for street use (C/C-SiC via LSI): For the most part, ceramic brakes are used in luxury and sports cars for brake pads and brake discs. Factors such as durability and efficiency play a major role. It remains to be seen whether ceramic brakes will become established in mid-range vehicles. Due to their low weight, the use of simple ceramic brake discs without sophisticated internal ventilation is certainly possible in lightweight vehicles with high innovation potential (for example, in pure e-vehicles).

Carbon-ceramic brake pads or discs achieve high and consistent friction values, regardless of surface moisture and temperature, meaning there is no fading effect.

Graphic representation of a fictional vehicle brake @ Ceramic Composites and @ Audi

Ceramic brake @ Brembo SGL Carbon Ceramic Brakes

They last a very long time, a car's life under normal driving conditions (up to 300,000 km are quoted by manufacturers). Thanks to the corrosion resistance of the material (no salt corrosion in winter), the life of the brake disc is extended. They are also up to 70 % lighter than conventional brake discs. This reduces the weight of the chassis and means a reduction in unsprung masses with an improvement in the road contact of the wheels. Furthermore, the brake offers a very low density combined with high specific strength, although the absolute strength values of these ceramics are lower than those of steel.

One of the disadvantages, however, is that the CMC brake currently has significantly higher production costs than the conventionally used metals. This is due, among other things, to the more complex production, but also to the smaller market volume. Furthermore, under heavy load, ceramic discs begin to glow like conventional brake discs. Since they can withstand much higher temperatures (1,300 °C) than metallic discs, the immediate environment of such brake discs must be prepared for this temperature level, which is ensured by brake system manufacturers through design measures.

Racing brakes (C/C via CVI): In motorsport, especially in Formula 1, brake discs made of carbon fiber reinforced carbon (C/C) are used. The difference between high-performance brakes in motorsport is not so much the basic composition of the components, but rather their specific set-up, which is designed to meet the requirements of a racetrack.

The advantage of these brake discs lies in their performance combined with their low weight. Technically speaking, the performance of C/C brake discs is brought about by an above-average coefficient of friction of 0.6. As a result, Formula 1 cars achieve braking decelerations of up to 5 g. By way of comparison, a perfect emergency braking manoeuvre with a series-production passenger car on a surface with good grip enables a braking deceleration of around 1 g.

Another advantage is the very low weight of carbon disc brakes, which is about 50 per cent less than comparable brakes made of grey cast iron. The weight reduction not only lowers the unsprung masses, which ensures better suspension response, but also lowers the rotating masses on the wheel, which improves steering behaviour.

C/C Racing Brake @ SGL Carbon

Formula 1 Brake @ SPOX

Clutch Discs @ Toyo Tanso

However, the positive characteristics of carbon disc brakes are also accompanied by disadvantages. First and foremost, the price of such brakes stands in the way of their widespread use in large-scale production. In contrast to the brakes in a production car, the components used in Formula 1 also wear out very quickly. In concrete terms: a Formula 1 team uses several sets of brake discs and brake pads every race weekend. It is therefore not surprising that the brakes on a Formula 1 racing car are a major cost factor.

Carbon friction linings (C/C via CVI) for wet running are often found in synchroniser rings. The increase in automated transmissions, especially dual-clutch transmissions, has made carbon friction materials an integral part of modern synchronisers over the last decade. These C/C friction materials consist of a carbon fiber fabric embedded in carbon. The carbon matrix encloses the fibers and thus protects the fiber from wear. The porous system structure simultaneously ensures excellent oil management.

3.2 Aviation

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

3.3 Space

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

3.4 Defence

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

3.5 Engineering

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

3.6 Others

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

3.7 Possible Future Scenarios

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

4 Market volumes

4.1 Introduction

In order to enable a better comparability with other market reports and to assure a higher plausibility of the shown information, the two most common growth rate factors and their calculations are summarised in the following:

Averaged Annual Growth Rate (AAGR) = Arithmetic Mean Return (AMR) = Arithmetic Average from n annual growth rates (AGR):

$$AAGR(t_1, t_n) = \frac{AGR(t_1) + AGR(t_2) + \cdots + AGR(t_n)}{n} = \frac{1}{n}\sum_{i=1}^{n} AGR(t_i)$$

Compound Annual Growth Rate (CAGR) = annual growth rate over n years assuming a proportionally constant growth:

$$CAGR(t_1, t_n) = \left(\frac{A(t_n)}{A(t_1)}\right)^{\frac{1}{n}} - 1 \quad \leftrightarrow \quad A(t_n) = A(t_1)(1 + CAGR)^n$$

Since the research for this report began as early as 2019 and the work took more than 3.5 years, the calendar year 2021 is always selected here as the starting time frame for the observations. Constantly changing data also in 2022, especially the Covid pandemic but also the war in the Urkaine is always considered in the scenario considerations.

The exact quantity of oxide and non-oxide ceramic fibers produced can only be estimated at present, since the manufacturers do not publicly provide any or only very few details on this. However, as already described in chapter 1.3, the data collection was carried out by means of differentiated and reliable observation. The authors currently assume that the figures given here should not fluctuate by more than 15 % upwards or downwards.

4.2 Oxide Fiber and Ox/Ox

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

4.3 SiC Fiber and SiC/SiC

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

4.4 C/C

The carbon carbon (C/C) market is much more difficult and intransparent to describe than the Ox/Ox and SiC/SiC markets. On the one hand, this is due to the large number of players who are active here. On the other hand, the growth in China in recent years has been enormous in this area. At the same time, however, little reliable information is leaking out about where China is active in the market. There are several transparent applications that are known worldwide and in the Chinese market, such as batch carriers for plasma-enhanced chemical vapor deposition. Also quite well known are the tonnages in the field of C/C of the semiconductor industry, solar industry, the production of polysilicon, crystal pullers and many more, also compare chapter 3. In addition, there are also several military applications from C/C, which are not as well documented. Even the authors mentioned here do not have an all-encompassing overview of the C/C market. Therefore, the C/C numbers mentioned below are to be interpreted with a certain range of variation.

The main application for C/C is by far the aircraft brake. Depending on the region (western world, Asia, Africa), type of aircraft (large passenger aircraft, small aircraft < 10 passengers, cargo aircraft), there are different expressions about the use of C/C aircraft brakes. In small passenger aircraft, metallic brake discs are mostly used. Outside the western world and in the cargo sector, up to 40 % metallic brake discs are still used on larger aircraft. In the passenger sector of the Western world, carbon/carbon brakes have become almost exclusively established for aircrafts > 10 passengers.

The service life of a C/C aircraft brake heat pack depends heavily on the load. Each airline has its own standards here. Brake discs are replaced according to the degree of wear, for one thing. On newer aircraft, wear is measured electronically; on older aircraft, wear is measured mechanically, via a control pin. Furthermore, each brake also has a maximum number of landing cycles that can be performed. Therefore, the service life of a heat pack varies greatly depending on whether an aircraft lands seven times a day or once. Most aircraft therefore receive new heatpacks every four to 18 months, depending on the amount of landing manouvers.

Most heatpacks consist of 9 - 11 discs, depending on the size of the heatpack. Of these, 5 discs (or 6) are stators, and 4 discs (or 5) are rotors. The size of the discs varies depending on the aircraft from 5 to almost 8 kg / disc. Furthermore, the heatpacks are also maintained and reurbished. Thus, braked heatpacks on small aircraft, e.g., Airbus A319 are given a second life with the help of distanced disks, while on larger brake disks, low-braked disks are removed, ground down and joined with another disk. It can therefore be assumed that approx. 50% of all C/C brake discs experience a second life, which in some cases is significantly shorter than the first life.

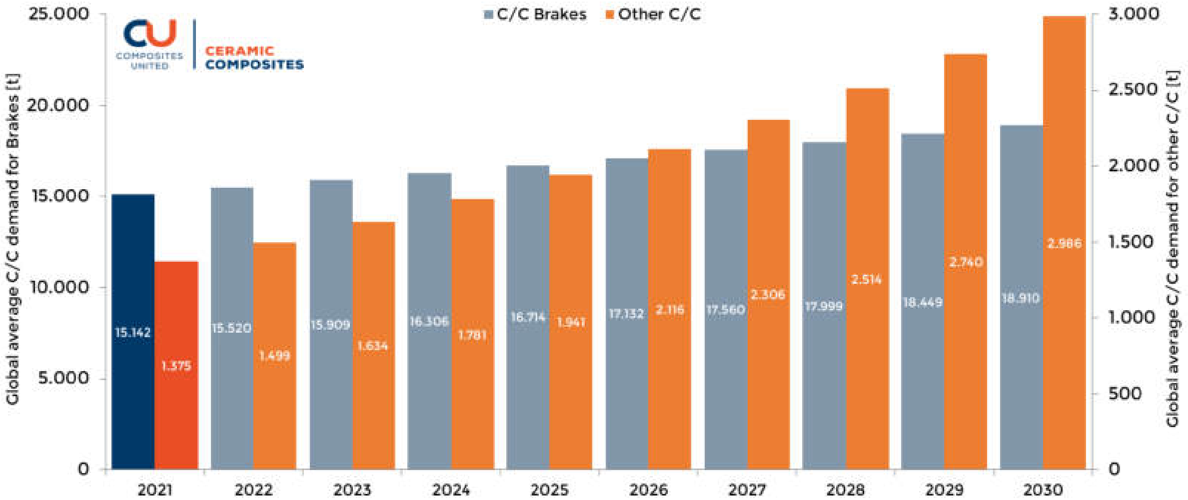
In addition to numerous interviews with airlines, aircraft technicians and aircraft manufacturers, the authors also counted the number of aircraft in service. Enclosed is an overview of the aircraft currently in service:

Aircraft	# Heatpacks	# Planes
Airbus A220	4	173
Airbus A300	8	561
Airbus A310	8	255
Airbus A318	4	60
Airbus A319	4	1381
Airbus A320	4	5637
Airbus A321	4	2330
Airbus A330	8	1437
Airbus A340 -200/300	10	214
Airbus A340 -500/600	12	131
Airbus A350	8	440
Airbus A380	20	243
Antonov An-124	22	33
Antonov An-148/An-158	4	32
ATR 42/72	4	970
Boeing 707	8	0
Boeing 717	4	93
Boeing 727	6	0
Boeing 737	4	7728
Boeing 747	16	426
Boeing 757	8	629
Boeing 767 und KC-46A Pegasus	8	754

Boeing 777	12	1347
Boeing 787	8	931
Boeing C-17A Globemaster III (Defence)	12	278
Bombardier BD-100 Challenger 300	4	unknown, max 290
Bombardier CRJ100 /CRJ200 / CRJ400	4	564
Bombardier CRJ1000	4	64
Bombardier CRJ700	4	298
Bombardier CRJ900	4	469
Bombardier DH8 / De Havilland DHC-8 (Q-Series)	4	847
British Aerospace BAe 146/Avro RJ	4	137
British Aerospace BAe ATP	4	15
COMAC ARJ21	4	57
COMAC C919	4	6
Dornier Do-328	4	115
Douglas DC-8	8	7
Embraer E2	4	54
Embraer ERJ-145	4	787
Embraer ERJ-170	4	769
Embraer ERJ-190	4	619
Fokker F50 / F60	4	117
Fokker F70 / F100	4	119
Ilyushin Il-96	12	16
Lockheed C-5 Galaxy	26	52
McDonnell Douglas DC-10/MD-11	4	234
McDonnell Douglas DC-9/MD-80 Series/MD-90	4	134
Mitsubishi MRJ90	4	5
Saab 2000	4	23
Saab 340	4	220
Sukhoi Superjet 100	4	52
Tupolev Tu-204	8	18

As described above, not every aircraft has a C/C brake. And not every C/C brake is identical. There are numerous variations in the design. However, for market estimation it is crucial: Which wheels or wheel pairs have a heat pack, how many C/C discs are in the heat pack and how large are these discs. Since all these assumptions vary greatly, the C/C figures are also subject to a certain degree of uncertainty. A fluctuation range of +/- 10 percent should always be considered.

The above assumptions on the tonnage of brake discs were verified independently but consistently by several experts. It can therefore be assumed that around 16,000 metric tons of C/C were manufactured in the reference period 2021, which were used exclusively in aircraft brakes. To this end, the aircraft brake market is still likely to grow strongly in the 20s of the 21st century. On the one hand, airlines are expecting a considerable increase in air traffic, and on the other hand, C/C brake discs are increasingly replacing metallic brake discs. Nevertheless, the volume of C/C brake discs for aircraft is growing at a disproportionately lower rate. This is mainly due to new technologies for refurbishing these discs. Some aircraft brake discs are reconditioned and reused even today. The reused disk is also often used in other aircrafts, such as cargo, where failure of a single heat pack would result in less damage. An expansion of repair and refurbishment concepts is therefore to be expected, not least because of the high production costs.



The rest of the carbon/carbon market is only about $^1/_{10}$ as large as the aircraft brake market in the period under consideration. However, the remaining carbon/carbon market is growing at a significantly higher rate than the market for aircraft brakes. China in particular will produce more than 50 % of all C/C products that cannot be assigned to aircraft brakes in 2030.

Currently, the largest markets for carbon are the semiconductor and solar industries as well as military technology. Smaller areas of application are other friction applications such as emergency brakes for elevators or trains. However, these brakes are also manufactured from C/SiC (Chapter 4.5). The strong growth worldwide, but especially in China, is attributed to the solar industry and its associated applications.

Sales in the C/C area vary greatly depending on the products used. Production costs can be estimated between 50 € and 300 € per kilogram of component for most series applications. The turnover with the products obtained is incomparably higher. Total global sales in 2021 are estimated at around 6 - 8 billion € and should roughly double in the next 10 years.

4.5 C/SiC

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com.

4.6 Summary

This is exclusive content of the extended version of this market report. To obtain the extended version, please contact market.report@composites-united.com. The text is shortend.

Compared to polymer matrix composites (GFRP, CFRP, etc.), CMC are still a strong niche material. Even the major applications of vehicle and aircraft brakes are rather small in terms of quantity compared to all other materials. However, what characterizes CMC in total are the strong growth trends, especially in the SiC/SiC area. This is partly since CMC are increasingly in demand either as strategic - military material, but also that CMC in its entirety in the technologies of the megatrends to hold. Be it in the field of energy conversion and storage, in the field of mobility, flying and many more. In many new applications CMC are considered as enablers for new developments.

In terms of volume, one can clearly see that C/C is predominant today with 17,000 tons per year, followed by C/SiC, Ox/Ox and SiC/SiC. This trend can also be seen in the sales figures, although all sales figures tend to represent an average value. C/C accounts for just under 80% of sales, followed by SiC/SiC, C/SiC and Ox/Ox. The relatively high sales of SiC/SiC compared to the very low tonnage are due to the very high material prices, which should, however, decrease in the next few years.

It remains to be seen what the future will bring. Whether the high growth trend of SiC/SiC will hold is certainly also a question of the cost reduction of the fiber. At the same time, it is not possible to reliably say today what air traffic will look like in 2030 or 2040. No one knows today whether petroleum-based flights will still be possible, whether sufficient e-fuels will be available, or whether the aero-gas turbine including its SiC/SiC components will be replaced by fuel cell drives or battery-electric flying. All the assumptions made here for SiC/SiC assume that the airline industry will grow exactly as predicted by airlines, engine, and aircraft manufacturers. Effects of climate change or various protest movements (e. g. Fridays for Future) do not play an overriding role in the analysis.

The exciting large potential applications of Ox/Ox in chemical and plant engineering, to produce green hydrogen and in electromobility are also growth markets. The question is whether fiber producers will be able to establish resilient supply chains at low selling prices.

5 Summary

This CMC market report has taken a different approach than commercially available CMC market reports to date. By involving a large number of authors, each of whom is an expert in the field of CMC, many other market reports could be critically evaluated and classified. For this purpose, bottum-up component analyses were cross-checked with current publications and tested for plausibility. In the process, considerable discrepancies in the data situation with commercially available reports emerged. Not all discrepancies could be finally eliminated. In this report, for example, only what is virtually certain knowledge has been published.

First, the current players in the CMC market were presented. This is also intended to provide an overview of which companies are already active here and where these activities mainly dominate. Then the main applications of CMC were described. Divided by industries, such as aerospace, automotive, etc., the series applications from SiC/SiC, Ox/Ox, C/C and C/SiC were described and differences pointed out.

Chapter 4 then broke down production volumes by material and some by application. In addition, global sales revenues were estimated. In the knowledge that most market reports go into much greater detail here, this market report has held back in sales. The main reason for this is that a company's sales cannot usually be directly linked to the material CMC.

So, the conclusion of this report remains: Series applications from CMC are currently being strengthened and further expanded (Chapter 4). In addition, new series applications are likely to enter the market, which are not yet being produced in large quantities today (Chapter 3). The growth rates can be assessed very differently depending on the material and the market. From disproportionate growth in the SiC/SiC area - i.e., more growth than market development would suggest - to mixed ratios depending on the applications in the C/C area. Positive price developments on the one hand, but also the establishment of recycling, refurbishment, and re-use concepts on the other, lead to various future scenarios.

6 Outlook

In the future, several breakthrough leap innovations are expected in the CMC world. Numerous new production lines are being created, and new applications for CMC are regularly found. The following topics are likely to emerge:

Technology transfer: Vehicle (C/SiC) and aircraft brake (C/C) technologies are likely to be transferred to new applications. Large-scale production capability has already been demonstrated here. New braking concepts are also being developed in electromobility. C/SiC from aerospace is finding more and more applications in other industries, SiC/SiC is used as a material not only in turbines and nuclear reactors. Ox/Ox will also move from the military, through heat treatment, into more and more new applications through new fibers and series production. The technology transfer that other materials have taken from high-tech to mass application is also about to happen to CMC's wide range of materials.

Sustainability: Already today, a few approaches exist to produce CMC a little more sustainably in production. From the use of renewable energy sources to "green" precursors for the fibers and matrices, to recycled materials. Politically, but also socially, the trends are moving towards clean technologies and materials. Particularly in the highly energy-intensive manufacturing process, considerable amounts of environmental pollution can still be saved. In some cases, with little or no loss of component performance. Along with the energy and raw material savings, production costs are also reduced as a matter of course. Particularly among the members of Ceramic Composites, a pioneering role is being played here.

Recycling and **repair**: More and more CMC applications are already being refurbished or repaired. This reduces the need for costly and time-consuming new production. Furthermore, new recycling routes are currently being established so that CMC can be kept completely in the materials cycle in the medium term.

Developments in these trends remain to be seen. There is certainly enough material for a revised edition in a few years.

- Your authors -

CU
COMPOSITES UNITED

CERAMIC COMPOSITES

CMC MARKET REPORT – THE GLOBAL MARKET FOR CMC

Authors:

Denny Schüppel | Dr. Hagen Klemm | Linda Klopsch
Prof. Dr. Dietmar Koch | Michael Kühnel
Michael Sauer | Dr. Florian Reichert | Arne Rüdinger
Dr. Clemens Steinborn | Dr. Michael Welter

Ceramic Composites – Network of Composites United e. V.

Am Technologiezentrum 5
86159 Augsburg | Germany
www.ceramic-composites.com

Status: April 2023