Silicon Carbide and Silicon Nitride Ceramics for Passive Structural Components in Avionics, Space and Mechanical Engineering

Silicon nitride and silicon carbide components for avionics, space and mechanical engineering are described. These lightweight stiff and strong materials with low and very low CTE and high thermal conductivity provide means for new designs and higher resolution in passive structures for optical instruments and wear resistant parts for mechanical engineering. Material properties and application examples are discussed.

Introduction

Silicon nitride and silicon carbide ceramics are gaining more and more interest in avionics and space, because of lightweight stiff and strong materials with low and very low CTE and high thermal conductivity are highly requested to push frontiers to higher resolution in telescopes.

Due to the excellent combination of properties, dense sintered (SSN), gas pressure sintered (GPSN), hot pressed (HPSN) or hot isostatic pressed (HIPSN) silicon nitride and sintered silicon carbide (SSiC) ceramics and composites are candidate materials to fulfill design and optical engineers requirements. Truss structures and spiders for telescopes, instrument base plates, lightweight mirrors as well as housings for telescopes and gyros made of silicon nitride and carbide have been approved and got into flight model serial production.

Silicon nitride and silicon carbide at FCT

FCT Ingenieurkeramik GmbH is developing and producing silicon nitride and silicon carbide materials since about 25 years. Now a newly developed family of silicon nitride and silicon carbide ceramics is available in even large and complex shaped components. With a CTE of down to <1,4 × 10^{-6}/K, thermal conductivity of up to 85 W/m · K at 20 °C, 4-point bending strength of up to 1100 MPa and the ability to get polished to optical grade mirror surface without coating. Also highly dense, highly strong and fine grained sintered silicon carbide, with a thermal conductivity up to 150 W/m · K and bending strength up to 500 MPa, either as electrical insulator or conductor can be offered.

These materials have opened new fields for further application in avionics and space. Such newly developed ceramics in combination with advanced fabrication technologies, allowing also rather large, lightweight and highly complex designed structures with high precision and smooth surface roughness show potential, to outperform the actually mainly used silicon carbide grades, and – moreover with silicon nitride –, add a new material with very promising properties and application options. It could be an alternative to metals, carbon fiber composites and ceramics, in aviation and space instruments as well as for terrestric applications.

Components made of these materials are available on a commercial base with diameters up to 500 mm and length up to 1300 mm. The material thickness ranges from 0,125 mm up to 70 mm at mayor properties of those silicon nitride and silicon carbide grades are presented in following table in comparison with materials which are used in avionics and space structures.

Silicon nitride with high thermal conductivity

In order to overcome the lack of high thermal conductivity, which for standard grades of silicon nitride is poor, compared to silicon carbide, grades with increased thermal conductivity have been developed, keeping the high strength and fracture toughness as well as the very low CTE.

Keywords
silicon nitride, silicon carbide, avionics, space, mechanical engineering

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Tab. 1 Properties of ceramics used for lightweight structures in avionics and space instruments (Si_3N_4 and SSiC grades from FCT in bold)

	Material		Density	Young	CTE	TC	4PBS	Tough
			ρ [g/cm³]	E [GPa]	α [$\times 10^{-6}$/K]	λ [W/m · K]	σ [MPa]	K1c [MPa $\sqrt{}$ m]
	SiO_2	Zerodur/ ULE	2,21	91	0,03	1	32	2
Silicon Nitride Ceramics	**Si_3N_4**	**SN-GP**	**3,25**	**310**	**1,4**	**25,**	**750**	**6,5**
	Si_3N_4	**SN-TC**	**3,32**	**310**	**1,5**	**85**	**750**	**7,5**
	Si_3N_4	**SN-TCHP**	**3,34**	**320**	**1,5**	**65**	**1050**	**7,5**
	Si_3N_4	**SN-PU**	**3,21**	**330**	**1,3**	**25**	**1020**	**6,5**
	Si_3N_4	**SN-TN**	**3,45**	**350**	**1,6**	**25**	**950**	**7,5**
Silicon Carbide Ceramics	**SiC**	**SC-S**	**3,14**	**430**	**2,2**	**145**	**510**	**4**
	CESIC®	HB	2,95	350	2,3	145	320	3,7
		MF	2,65	249	2,1	121	149	4,6
	SiSiC	90	3,1	380	2,5	140	290	3,5
	SiSiC	80	3,03	360	2,4	150	290	3,5
	SiC	LPS	3,25	410	2,6	90	500	5
	SiC_f/SiC	CVI	2,6	200	2,5	18	500	15
Various Others	B_4C		2,5	410	4,8	28	500	3,5
	Al_2O_3	S Cryst	4	400	6	20	450	4
	Al_2O_3	SiCw	3,75	390	5	40	500	8,5

State of the art now is shown in Tab. 1. FCT achieved several grades, densified by either uniaxial hot pressing or gas pressure sintering with thermal conductivities from 45–85 W/m · K. The lower values reached by hot pressing show very high strength values up to 1150 MPa. The gas pressure sintered grades reach up to 85 W/m · K at a strength level of 750 MPa and still high fracture toughness. CTE is still at a very low value, much lower than the ones for silicon carbide. Some grades are already available as components, other are still only in lab scale sample size.
The FCT silicon nitride grades, – already produced since many years – and the newly developed, optimized and partially qualified for avionics and space, offer sig-

Fig. 1
Housing structure and final assembly of an avionic reconnaissance telescope camera

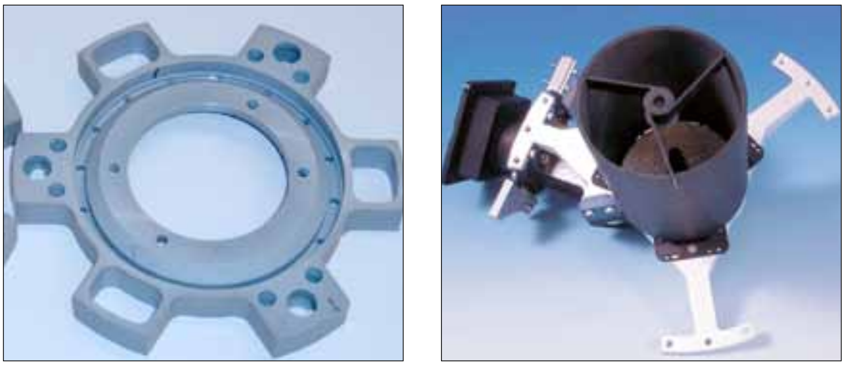


Fig. 2
Spider base for small communication satellite of Si_3N_4

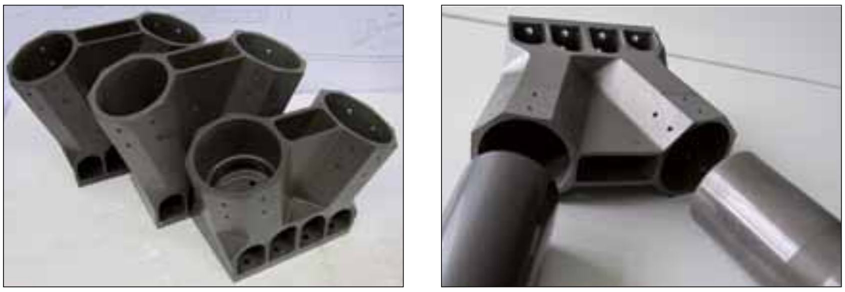


Fig. 3
Beam connectors and beam ends of truss structure of large satellite

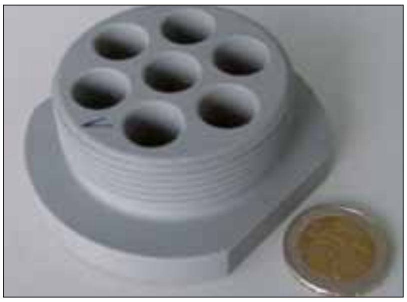
Fig. 4
Backside rib stiffening segment of lightweight SSiC mirror

Fig. 5
Silicon nitride spring rings, ball and socket joint

nificantly increased mechanical performances in regard to strength and fracture toughness compared to silicon carbide and glass ceramic materials, which may also help to get much higher reliability in components.
Another parameter is the CTE of silicon nitride grades which is always much lower than all the ones of silicon carbide grades and all other high strength and tough ceramics.
FCT additionally works on composites of nitride and carbide in order to increase both, TC and Young's modulus in combination. Latest approaches are composites with silicon nitride and diamond, where initial samples show TC values above 100 W/m · K and Young's modulus in the range of 400 GPa. And the hardness caused enormous problems in machining.

Avionics and space experience
Since about eight years FCT started to produce and supply ultra light weight highly stiff structures with very low CTE silicon nitride ceramics for airborne reconnaissance telescope camera systems.
Since 2006 FCT is in progress to qualify silicon nitride also for space telescopes. Some facts are described in cited literature. Qualification of scale 1 preflight components was reached in 2010/2011 and since then we are qualified supplier for space structures.
By end of 2013 FCT has supplied all the flight model components for two space instruments having a silicon nitride truss structure. This structure is made of specific lightweight beams and beam connectors. Their final integration into the space instrument is ongoing.

Silicon carbide
FCT also has even long term experience with sintered silicon carbide. Also here, FCT offers a wide range of components for mainly wear and corrosion applications in chemical, mechanical and high temperature engineering.
Since end of 2013 FCT is in progress to also qualify the FCT sintered silicon carbide (SSiC) grades for lightweight passive components in space instruments.
Because of its high stiffness, the still very small CTE and the very high thermal conductivity, SSiC is a candidate material for lightweight mirrors. Initial work is done at



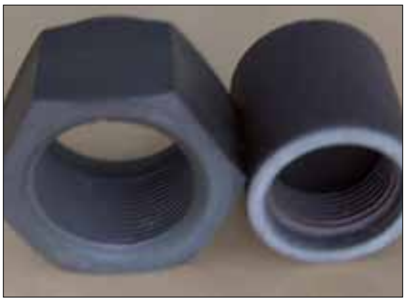


Fig. 6
Nuts and bolts with thread made of silicon nitride and silicon carbide

FCT to produce prototypes for the evaluation and validation of both, process and material grade. Beside the production of the lightweight mirror structure of SSiC, the optical face has to be coated with a layer of fully dense CVD/SiC in order to close all individual micropores which are inherent for SSiC ceramics.
This fully dense SiC layer can then be machined to requested curvature and highly shining and reflecting optical surface finish for visible and infrared light spectrum. Because both elements are of SiC, the mirror can also work under cryogenic conditions.

Fig. 7
Tubes and profiles of SSiC and Si_3N_4

Other components and applications
Also weight saving is the replacement of steel balls in ball joints by silicon nitride. It also prevents corrosion.
Mainly in high temperature applications and in corrosive media, the use of bolts and nuts wit threads have helped to facilitate highly effective and reliable installations and fixations. Here steel, other metals, graphite, carbon fiber composites and polymers are replaced.
Also for high temperature engineering we do quite a bit of tubes, beams and profiles with silicon nitride and silicon carbide which are highly stiff and lightweight – low thermal mass –, are thermal shock resistant and can be used up to temperatures of 1400 °C for silicon nitride and 2000 °C for silicon carbide.
In some applications Ni-based alloys like HASTELLOY are replaced or even noble metals like platinum and palladium e.g. in high temperature applications running up to 1200 °C with very strong thermal, chemical corrosion and creep requirements.
Another application is electronics and specifically wafer handling and testing. Here, mainly disc like shapes are required with diameters up to 420 mm and thickness ranging from 0,125 up to 20 mm. These discs typically have to be ground and lapped or even polished.
With hot pressed grades, polishing to optical grade surface finish without any coating can be achieved. This is caused by the fully densified, homogenous, void free microstructure. Silicon carbide always shows micro pores and/or carbon particles as imperfections.
The discs are used as wafer support or as wafer probe cards. Then up to 20 000 holes

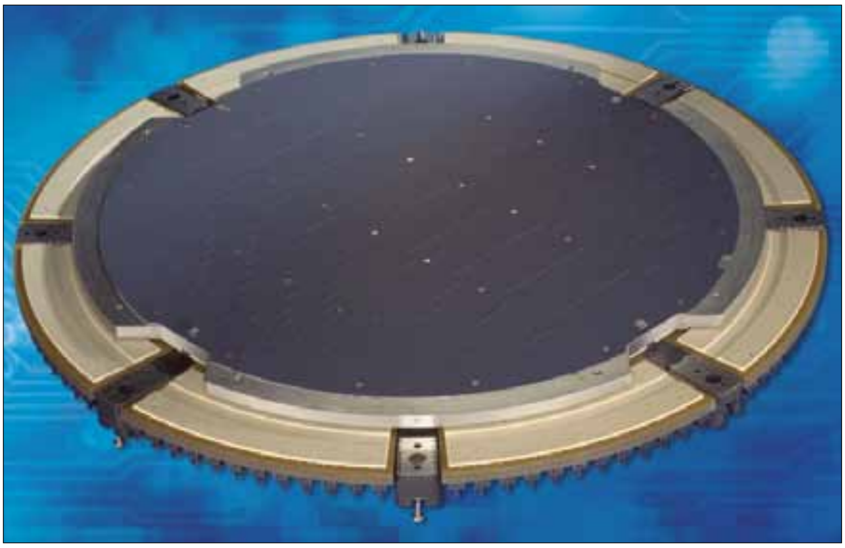


Fig. 8
Wafer probe card

Fig. 9
Wafer handling jug insert

Fig. 10
Vibrational shaker head for calibration shaker made of silicon nitride

are drilled by laser milling where the contact tips are then be feed through.
Another application is in power electronics specifically for highly mechanically and thermally stressed substrates. Here, mainly disc and plate like shapes are required with diameters up to 420 mm and thickness ranging from 0,125 up to 2,0 mm. These discs and plates typically have to be ground and lapped or even must be polished.

With hot pressed grades of silicon nitride, direct polishing to optical grade surface finish without any coating can be achieved. This is caused by the fully densified, fine grained, homogenous and void free microstructure.
Silicon carbide always shows micro-pores and/or carbon particles as imperfections and therefore requires coatings when used as mirror.

With the use of silicon nitride for vibrational shaker heads, the test frequency could be doubled to 25 kHz and we additionally got the feedback, that there is no cycling fatigue for the silicon nitride ceramic since test equipment is in operation since many years with no degradation of frequency.
Using silicon nitride as spring material, e.g. in spring rings, the weight is less than half and it still keeps elasticity at up to 1100 °C and in very corrosive media.
Also weight saving is the replacement of steel balls in ball joints by silicon nitride. It also prevents corrosion.

Conclusions

Silicon carbide ceramics in different compositions and grades, out of various processing routes are already widely used in avionics and space.
Silicon nitride is new and unique for this application, although it shows some properties like mechanical strength and fracture toughness as well as a very low CTE, – much lower than for silicon carbide grades – which can outperform the today used material.
One mayor constraint is up to now however the limited size of components, which should be typically less than 1,7 m in length and less than 700 mm in diameter. Another constraint is the fact, that silicon nitride could not be coated with CVD/SiC for getting a void free surface for mirrors.
But one grade of silicon nitride is now qualified for truss the structure of a rather large optical satellite and components for flight instrument were produced at FCT and are in progress of integration into the space instrument. On the other side, the housing structure for the avionic reconnaissance camera is successfully flying since about at least eight years now.
An initial attempt, to also qualify FCT sintered dense silicon carbide is started.

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