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Fraunhofer Institute for Ceramic Technologies and Systems IKTS

Zirconium carbide components for high-temperature processes

Powerful, reliable and cost-efficient

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Content

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1. Zirconium carbide as an alternative to tungsten and molybdenum

Ever higher demands are being placed on the purity of process atmospheres and corrosive thermal and chemical stability for high-temperature processes in the semiconductor industry, micro- and nanoelectronics, photovoltaics, optics and materials production. Currently, tungsten and molybdenum are frequently used materials for these applications. Due to the limited availability and high prices of these refractory metals, alternative materials such as zirconium carbide (ZrC) are attractive for innovative solutions in plant engineering.

Zirconium carbide belongs to the group of metal-like ceramics. As is the case with very few materials, the vapor pressure is extremely low even at high temperatures of over 2000 °C. The high melting point (Ts > 3500 °C) enables use up to the highest temperatures. Zirconium carbide exhibits outstanding corrosion stability under non-oxidizing atmospheres. It is therefore ideally suited for high-temperature applications and its properties are at least equivalent to those of refractory metals used to date.

In addition to its outstanding material properties, zirconium carbide is also lighter, less expensive and contains no critical raw materials. Nevertheless, it has not yet been used because the production of large-format and dense ZrC materials has not yet been technically possible. However, with a reliable and cost-effective manufacturing technology, this material would be an attractive alternative to many refractory metals.

2. Cost-efficient and reproducible manufacturing processes

Considering this background, a process was developed by which dense ZrC materials in different geometries can be produced cost-effectively by means of pressureless sintering. The coordinated combination of the technological steps enables the production of large-format ZrC components with a length of more than 250 mm. Plates and rods can also be produced. Such components can be used as electrical heating conductors, thermal protection, fluid lines or structural elements for high-temperature applications and thus improve the operating quality for high-temperature systems.

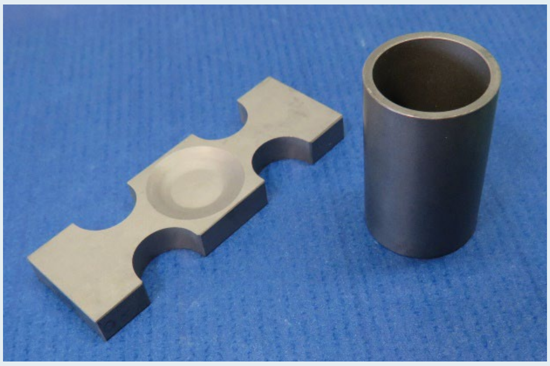

Figure 1: Evaporator and crucible material made of zirconium carbide.

Table 1: Comparison of conventional high-temperature materials with zirconium carbide.

Material	Advantages	Disadvantages
Tungsten	- Very high melting point (3420 °C) - Lowest vapor pressure - High creep resistance	- Increased susceptibility to fracture due to recrystallization - High manufacturing price
Molybdenum	- Low vapor pressure up to approx. 1700 °C - Lower manufacturing price than tungsten	- Maximum operating temperature < 1800 °C - Increased susceptibility to fracture due to recrystallization
Zirconium carbide	- Extremely heat-resistant up to 3500 °C - Low vapor pressure - Good corrosion stability	- Fracture behavior typical of ceramics - Strength lower than refractory metals

3. Material data and operating behavior of ZrC heating elements

Practical tests confirm the material a linear course of the electrical resistance up to 2000 °C, a high thermal stability, a high mechanical strength as well as a fracture toughness typical for ceramics on the level of silicon carbide. An overview of the determined material properties and a comparison with other heating element materials are shown in tables 2 and 3.

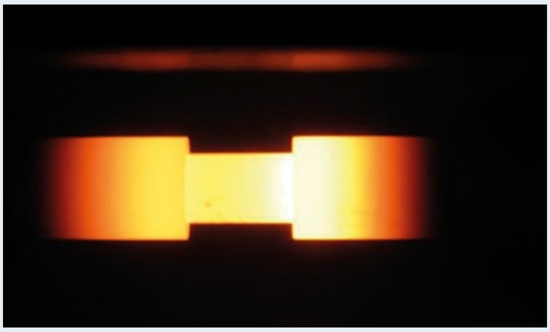

Figure 2: Measurement of the mechanical load capacity of a zirconium carbide heating element at high temperatures (10 kN, up to 1900 °C).

Table 2: Material properties of zirconium carbide heating elements.

Parameter	Value	Unit	Application facts
Density (theoretical)	6.73	$g \cdot cm^{-3}$	
Density (sintered)	6.63	$g \cdot cm^{-3}$	98.5 % of the theoretical density; ceramically practical complete compaction possible
Open porosity	0.05	Vol.%	No significant interactions with the environment
Melting point ZrC	3532	°C	Refractory material with higher melting point than tungsten (3422 °C)
4-point bending strength / RT	350–450	MPa	Usual strength of high-quality ceramic materials such as SiC
4-point bending strength / 1400 °C	150–230	MPa	High strength level even at higher temperatures; strength decreases with temperature
4-point bending strength after aging at 1900 °C at RT	350–450	MPa	No loss of strength due to thermal load
Fracture toughness	4	$MPa \cdot m^{1/2}$	Similar to SiC
E-modulus / RT	410	GPa	High stiffness, like SiC
Expansion coefficient / RT	5.4	$10^{-6} \cdot K^{-1}$	
Expansion coefficient / 2000 °C	7.1	$10^{-6} \cdot K^{-1}$	
Spec. electrical resistance / RT	$6.8 \cdot 10^{-5}$	Ωcm	Metal-like electrical resistance, relatively high
Spec. electrical resistance / 2000 °C	$2.1 \cdot 10^{-4}$	Ωcm	Moderate positive temperature coefficient
Thermal conductivity / RT	31	$W \cdot (mK)^{-1}$	Moderate thermal conductivity like Al_2O_3 or Si_3N_4
Thermal conductivity / 2000 °C	38	$W \cdot (mK)^{-1}$	Moderate increase in thermal conductivity
Spec. heat capacity / RT	0.355	$J \cdot (gK)^{-1}$	
Spec. heat capacity / 2000 °C	0.490	$J \cdot (gK)^{-1}$	

Table 3: Comparison with other heating element materials at 1800 °C.

Heating element data at 1800 °C	Tungsten	Molybdenum*	ZrC
Spec. electrical resistance [Ω*cm]	7.83E-5	8.56E-5	2.18E-5
Power [W]	4118	6731	5062
Power density [A/mm²]	25.7	30.9	16.4
Surface load [W cm²]	129	212	153

*Molybdenum mechanically stable only up to 1800 °C.

4. Reliable joining technology

By innovative joining technologies, zirconium carbide heating elements can be reliably integrated into the overall system. Alloys based on Fe-Si-Ti that have already been tested allow temperatures at the joining zone of > 1200 °C. The respective function of the ZrC components defines the requirements for the connection: electrical coupling, thermal insulation or conduction for system components, as well as mechanical stiffeners, supports or delimitations.

Figure 3: Copper rings as end contacts to zirconium carbide test specimens, shrinkage technique on metallized surface.

5. Advantages for the user

Zirconium carbide is very similar to the established tungsten components with regard to many properties. It achieves a comparably low vapor pressure in vacuum applications even at very high temperatures. The melting point of zirconium carbide is even higher than that of tungsten. The electrical and thermal conductivities are lower than those of the refractory metals tungsten and molybdenum, which is particularly advantageous for heat conductor applications or thermal composite structures. The newly developed technology for the sintering of ZrC components offers, above all, the opportunity to manufacture these products significantly more cheaply than the known refractory metal products. In addition, the availability of resources for raw material supply is safer and significantly larger compared to tungsten. In addition, zirconium carbide components offer further options for the design of high-temperature equipment resulting from their specific property profile. The modified thermal conductivity, different chemical reactivity, higher hardness and stiffness as well as the significantly lower specific mass allow new design principles, insulation strategies and increase reliability and uptime in certain processes.

Technical advantages of the ZrC solution

- Improved planning for maintenance and repair
- Avoiding the introduction of foreign materials into high-purity processes
- Increasing the reliability of quality control in the manufacturing process

6. Services and cooperation offered at Fraunhofer IKTS

With its zirconium carbide components, Fraunhofer IKTS offers a complete solution for heating elements for high-temperature applications:

- Material selection according to the occurring process parameters
- Production of heating elements in customer-specific dimensions
- Production of kiln furniture
- Production of targets and evaporator accessories
- Selection of the appropriate joining process and joining components
- Characterization of high-temperature resistant ceramics up to 2000 °C

Figure 4: Zirconium carbide heating elements for high-temperature processes.

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Fraunhofer IKTS in profile

For more than 30 years, Fraunhofer IKTS has been demonstrating the potential of ceramic materials in a steadily growing range of applications. It is our drive to develop complete system solutions and services, but also to solve specific challenges within the processes of our partners from industry and science. Our expertise in the characterization and analysis of materials, components and systems along their life cycle provides us with a unique data pool to carry out new developments more efficiently and faster.

Fraunhofer IKTS has a staff of more than 800 at its three main sites in Dresden and Hermsdorf as well as numerous external locations. This makes it the largest ceramics research institute in Europe. Researchers have access to 40,000 m2 of floor space with excellently equipped laboratories and pilot plants. These include both pilot lines suitable for industrial use and application centers in which new developments can be tested under conditions that are close to industrial practice.

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