Hot Stuff – Ceramics for Industrial Heating Applications

Electrical heating elements are used in innumerable industrial processes. They are used in plastics technology for heating injection nozzles, hot runners and tools, and in chemicals technology for melting and evaporating samples. In automotive engineering they are used, for instance, for the ignition of fuel mixes (hot surface igniters) and for heating sensors (e.g. λ-sensor). Other applications include industrial and laboratory furnaces, brazing and welding technology as well as various domestic appliances.

Fig. 1
Dr. Hannes Kühl presenting the heaters

Keywords
high-temperature ceramics, heating applications, heating elements, electrical heating, heating element supports, PTC heaters, high temperature heaters, tool-heating, heaters materials: cordierite, magnesium oxide (MgO), alumina (Al_2O_3), platinum (Pt), PTC ceramics, barium titanate ($BaTiO_3$)

Thanks to their outstanding high-temperature properties, ceramics are frequently used in these industrial heating applications. In some cases, ceramics make the realization of these applications possible in the first place.

Introduction
In the heating applications, a wide range of ceramic materials and products is used. A differentiation is made between applications in which the ceramics as "passive components" support the generally metallic resistance wires/heating conductors and act as an electrical insulator. Here, depending on the application, cordierite, magnesia or alumina is used. In ceramic heating elements, the ceramic itself functions, for example, as a heat conductor. In this case the ceramic must exhibit a certain electrical conductivity. In this context, PTC ceramics, SiC or mixed ceramics such as Al_2O_3/TiN, Si_3N_4/TiN, Si_3N_4/$MoSi_2$ etc. should be mentioned. Another group are the hybrid heating elements in which a metallic or electrically conductive ceramic conductor is sintered into the insulating ceramic.

The *Rauschert* group of companies is one of the leading manufacturers of technical ceramics worldwide and offers probably one of the most extensive product portfolios for industrial heating applications. In addition to classical ceramics such as cordierite or alumina, for these applications magnesia and PTC heating elements as well as high-temperature heating elements are produced for a temperature range to above 1000 °C.

Cordierite as a heating element support
Unlike "active" heating elements materials for heat conductors, the purpose of support materials for heating elements is to support the heating coils as they heat up even to very high surface temperatures; the coils are pulled over the heating element support or hung onto it. The preconditions for the ceramics used here are:
- high temperature resistance (higher than the maximum heating temperature)
- electrical insulation strength even at very high temperatures
- chemical resistance and corrosion resistance in the required atmosphere
- very good thermal shock resistance.

For this application, cordierite is an ideal material (Fig. 1). Cordierite is a magnesium-aluminium silicate mineral that ex-

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Fig. 2 and 3
Different cordierite products supplied by Rauschert GmbH

hibits a very low coefficient of thermal expansion. Accordingly, it also exhibits good thermal shock resistance. Cordierite ceramics are available in both porous and dense forms (Fig. 2– 3). Porous cordierite, labelled C 511, C 520 und C 530 in compliance with DIN EN 60 672-3, is used where pores have no adverse effect on the application. Such an effect may be, for instance, the ingress of moisture, which in time can lead to electric flashovers. Here dense cordierite (C 410) can be used. Depending on the type selected, cordierite can be used to a maximum temperature of around 1240 °C (C 520) or 1300 °C (C 530). Speciality grades with a high alumina or mullite content can be used to 1700 °C. These special grades, however, exhibit lower thermal shock resistance.
Cordierite ceramics are used for instance as heating conductor supports in industrial furnaces (helical coil cartridges), as winding, coil or grooved supports for resistance wires as well as multi-hole pipes in hot air blowers.

MgO for electrical heating applications
Another ceramic material for heating applications is magnesia, which is used as a filling material for heating cartridges of all types. Heating cartridges are generally structured as follows: resistance wires or heating spirals (usually NiCr wires) are embedded in a magnesia ceramic that functions as electrical insulation to the steel casing of the heating element.
Magnesia is the ideal material for this application. It has a very high melting point (>2800 °C) and besides good electrical insulation and high thermal conductivity, it exhibits high coefficients of expansion, roughly corresponding to that of steel. This has the advantage that all the materials in one heating cartridge expand to the same extent and no air gaps, which could hinder heat transfer, are formed. The selection and composition of the MgO raw materials has an enormous influence on the electrical insulation properties. Rauschert has many years of experience in the selection and combination of raw materials from different sources.
MgO for electrical heating applications is usually manufactured in the form of crushable tubes (Fig. 4). Extrusion is used for forming the tubes. With adjustment of the firing curve, it is possible to influence the strength of the MgO tubes and adapt them to customer requirements. The crushable tubes contain several end-to-end boreholes into which the resistance wires and coils are inserted.
Then the crushable tubes are placed into the steel casing and the entire composite is compacted by means of hammers, as a result of which the outer diameter can be reduced by around 20–25 %. In the compaction process the crushable tubes are pulverized so that the heating coils are embedded tightly in the magnesia. The strength of the crushable tubes produced therefore has an enormous influence on the crushing behaviour of the MgO tubes and the later quality of the heating elements. The crushable tubes have to be strong enough for handling and packaging, but soft enough for the compaction process. According to this principle, high-performance heating cartridges, heating cables, helical heaters, etc. are manufac-

Fig. 4
Various MgO components from Rauschert GmbH

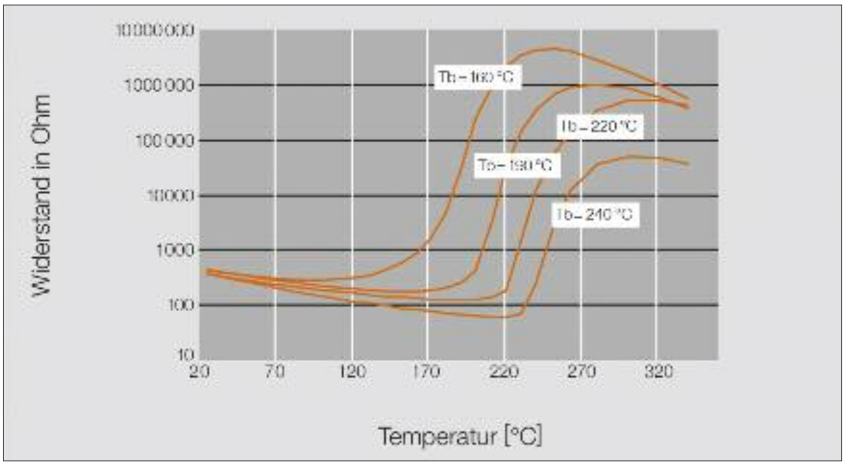

Fig. 5
Resistance jump at different Curie temperatures (ordinate: Widerstand/resistance[Ω])

tured in addition to heating cartridges. Heating cables, however, are not hammered but compacted in a drawing process. Here it is particularly important that the crushable tubes do not contain overly large or overly hard MgO particles as these can damage the resistance wire during the compaction process. Rauschert ensures this with a special screening process prior to manufacturing.
Detailed information on the use of MgO in thermal engineering is provided in [1].

PTC heating elements

Ceramic can also be used as an active heating material. PTC heating elements are one example. They consist of a semi-conductive barium titanate ceramic, which can also contain other components such as lead titanate or strontium titanate. Barium titanate gets its semi-conductive properties by means of doping with low amounts of lanthanum or other suitable substances. The key feature of PTC ceramic is that it is conductive up to a certain temperature, the *Curie* or transition temperature (Fig. 5). Above this temperature, the resistance of the material increases abruptly by several orders of magnitude within just a few *Kelvin*, as a result of which the material loses its conductivity. This effect is termed the PTC effect and results in a self-regulation of the heating element against overheating. The barium in the $BaTiO_3$ can be partially substituted with lead or strontium. In this way, the Curie temperature can be set in a range from around 50 to around 300 °C. Substitution with Sr effects a decrease in the Curie temperature and substitution with Pb an increase.
PTC heating elements are usually manufactured in the form of plates, disks or rings which are metallized on both sides for electric contact (Fig. 6). On account of their self-regulation behaviour, they are used in many fields. Applications include heating in car interiors (Fig. 7), heating for domestic appliances or control cabinet heating (Fig. 8). Here several plates are packed together to form a heating register. A range of 12–400 V is possible as the operating voltage. In the field of PTC heating elements, *Rauschert Hermsdorf GmbH* is one of the leading manufacturers worldwide.

High-temperature heating elements

If heating materials are needed for a higher temperature range than possible, for example, with PTC heating elements (max. approx. 300 °C) or heating cartridges (max. approx. 750 °C), several options are available:
Metallic heating wires made of NiCr can be used to around 1200 °C and FeCrAl wires up to 1350 °C. They are frequently used in

Fig. 6
Different forms of PTC heating elements

Fig. 7
Electric vehicle interior heating

industrial furnaces. For even higher temperatures, SiC (up to around 1600 °C) or $MoSi_2$ (up to max. 1900 °C) can be used. All these materials are suitable for use in an air atmosphere. In an atmosphere free of oxygen, even higher temperatures can be realized with the use of molybdenum or tungsten resistance wires or graphite heating elements. Up to 3000 °C can be achieved [2–9].

The many material developments that have been tested in recent decades for heating purposes, generally without commercial breakthrough, should also be mentioned here, e.g. doped $LaCrO_3$ [6, 10], doped ZrO_2 (theoretically maximum temperatures of 2200 °C achievable in air) [6–7], various silicides (e.g. Nb_5Si_3) [11] and other perovskites [12–13].

The materials just mentioned are manufactured either in the form of resistance wires (NiCr, FeCrAl, Mo, W) or heating bars ($MoSi_2$). $MoSi_2$ heating bars can be curved when hot to U- or W-shaped heating elements. SiC and graphite too are usually manufactured as solid components then structured by means of hard machining. Slits and grooves are sawen into the components to obtain the heating conductor structure. One essential disadvantage of these heating element forms is that they are not generally electrically insulated and accordingly not suitable for use in integrated industrial heating processes. For these applications, insulated metallic heating elements in the form of heating cartridges, helical coil cartridges, tubular heaters, etc. must be used. Up to a temperature of around 750 °C, these present a low-price option for integrated, electrically insulated heating. For higher temperatures or when very fast-reacting and durable heating elements are needed, hybrid heating elements are the first choice. These are heating elements that consist of metallic or ceramic heat conductors sintered into an electrically insulating ceramic. Possible material combinations here are: Al_2O_3/Pt, Al_2O_3/W, Si_3N_4/$MoSi_2$ as well as other combinations of these materials with Al_2O_3, Si_3N_4 or AlN as the insulating ceramic and Pt, W, $MoSi_2$, TiN, etc. as the heat conductor material [14–16].

Hybrid heating elements

Rauschert manufactures hybrid heating elements consisting of Al_2O_3 as the insulating component and platinum as the heat conductor material. The platinum heat conductor is sintered in the ceramic such that an inseparable "monolithic" component is formed that is completely electrically insulated on the outside. These heating elements can reach a temperature of around 1000–1100 °C in continuous operation or up to 1300 °C for short-term temperature peaks. Typical shapes are pipe-shaped (tubular) heating elements, so-called bar or ribbed heaters, or flat heating plates. Fig. 9 and 10 show different shapes.

The use of platinum as a heating conductor offers enormous advantages as platinum exhibits a completely linear resistance-temperature curve (Fig. 11). The platinum heat conductor can therefore be used simultaneously as a temperature sensor for measurement and regulation temperature of the heating element. If the

Fig. 8
Control cabinet heating

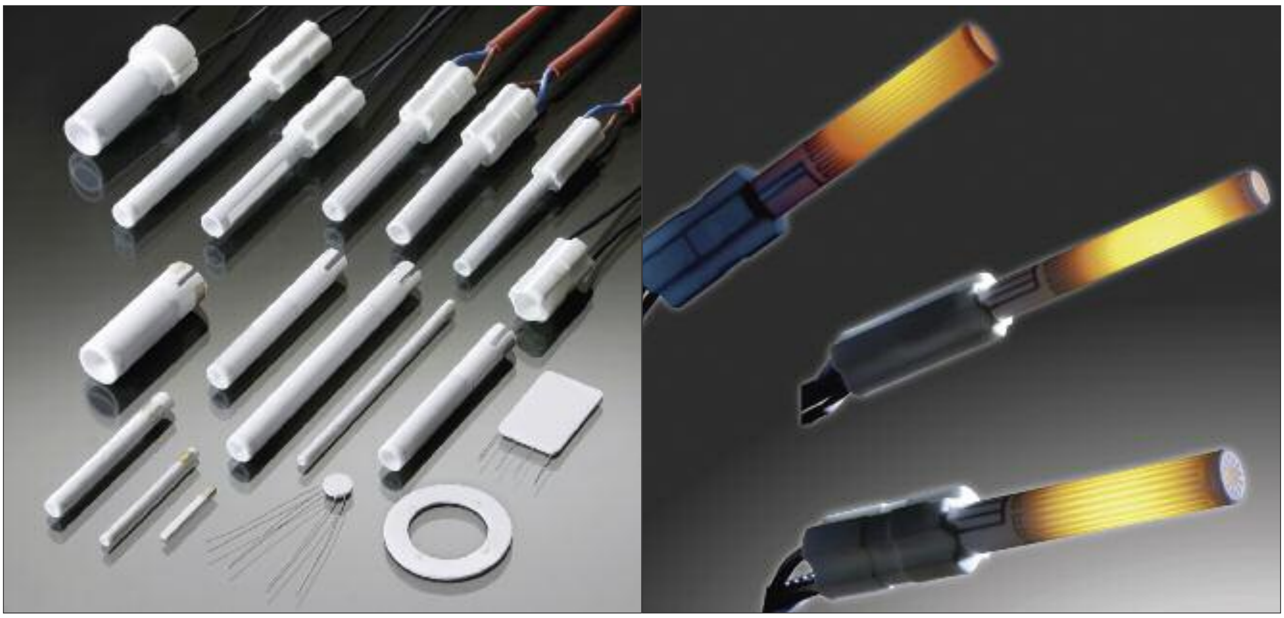

Fig. 9 and 10
Different models of hybrid heating elements from Rauschert GmbH

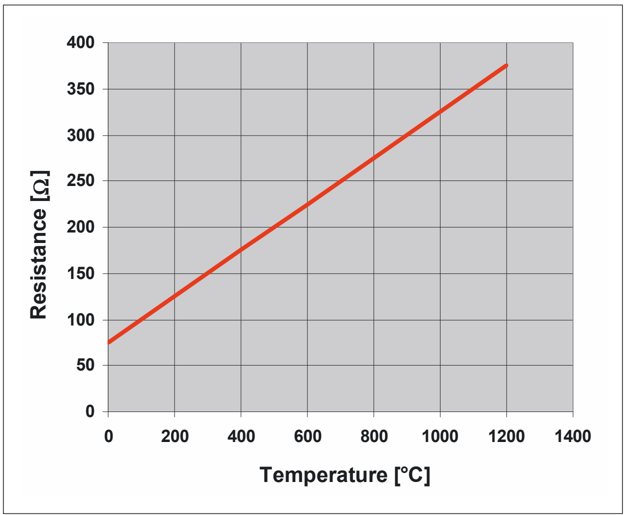

Fig. 11
Linear temperature dependence of the resistance of the Pt conductor

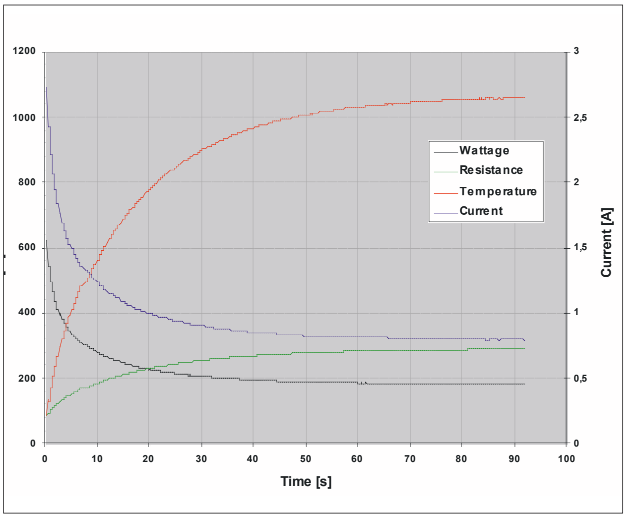

Fig. 12
Time curve of current, resistance, wattage and temperature on the switch-on moment (230 V AC)

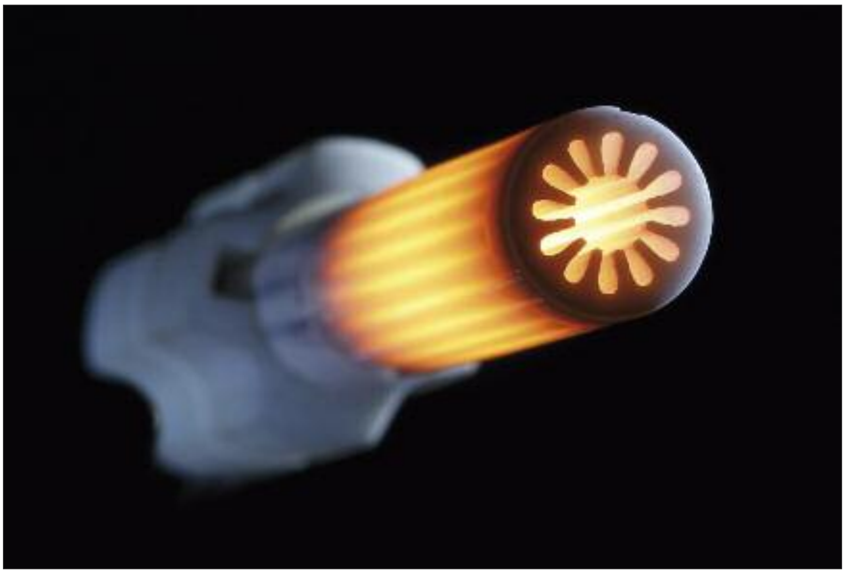

Fig. 13
Ribbed heater, fully electrically insulated from Rauschert GmbH for generating hot air (>900 °C)

heating and sensor circuit have to be electrically separated, a separate sensor circuit can be easily integrated.
Fig. 12 shows the time curve of current intensity, resistance, wattage and temperature after a 180-W heating element is switched on, i.e. voltage – in this case 230 V – is applied.
The operating voltage can usually be applied fully without any additional control at the switch-on moment. Owing to the positive temperature coefficient of the resistance, between room temperature and 1000 °C, the resistance can increase fourfold. As a result the temperature automatically regulates itself to the previously set value. An overheating of the heating element is excluded even without external regulation – another essential advantage of this system.
The lifetime and loadability (thermal shock resistance, constant heating and cooling) is very high. For a temperature of 1000 °C, several thousand operating hours or over 100 000 heating cycles can be achieved.
Rauschert supplies a wide range of products including standard heating elements to "tailored" heating solutions developed and designed in close cooperation with the customer [17]. The electrical data (voltage, current), the electric power, the temperature and component dimensions can be adjusted within a wide range. In the design of heating elements, Rauschert has extensive expert knowledge. Calculations are frequently backed up with FEA simulations. The temperature, temperature distribution and the electrical parameters such as power output, power consumption, etc. can be predefined precisely.
These heating elements are used wherever high process temperatures are needed:

- hot surface igniters (e.g. gas or oil ignition, pellet igniters)
- heaters for highest process temperatures (>700 °C)
- air heating
- tool/mould heating
- fusing/welding/soldering (heater for soldering irons)
- heaters for chemical analysis and process engineering (mini-furnaces, reactors)
- and much more.

Hybrid heating elements offer enormous potential for:

- miniaturization as they generate heat exactly where it is needed.
- energy saving as the heat loss to passive components is minimal (energy efficiency!).
- process time reduction as on the one hand, as a result of the low thermal mass of the ceramic heater, heat can be gener-

ated in a very short time and, on the other hand, as a result of higher process temperatures, processes such as welding or melting can be realized faster.

New developments in this field are special heating elements for heating air or gas (Fig. 13) [18]. Thanks to the higher inner surface area of these ribbed heaters, air fed through the heating element is heated to extremely high temperatures in a very short time. Air temperatures of over 900 °C can be achieved with enormous energy efficiency – i.e. with very low heating power. Applications include, for instance, hot gas soldering or melting of samples in chemical process engineering.

In chemical technology and analysis, hybrid heating elements are used as minifurnaces. Heating elements with an internal diameter of around 15–20 mm are used, installed vertically in the analysis apparatus. The sample to be tested is inserted into the hybrid heating element and be heated very precisely there. A sample temperature of up to 1100 °C can be reached within around five minutes. A range of physical properties and material data can be measured as a function of the temperature. Besides the steep heating ramp, a key advantage of the Al_2O_3/Pt hybrid heating element is the excellent chemical resistance, so that just about all atmospheric conditions (oxidation, reduction, air, N_2, H_2, argon, acidic gases etc.) without any detrimental influences on the heating element.

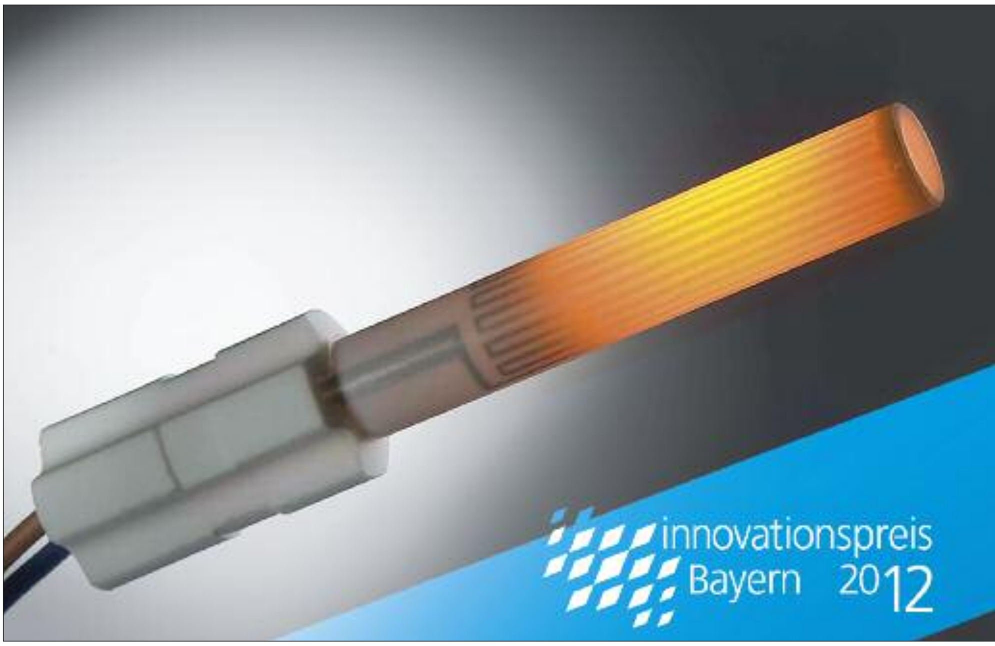

Fig. 14
Bavaria's Innovation Award 2012

The significance of the development of these heating elements was recognized with the presentation of Bavaria's Innovation Award 2012 (Fig. 14). Dr. Hannes Kühl, Development Manager at *Rauschert Steinbach GmbH*, and *Prof. Dr. Thomas Frey* from *Georg-Simon-Ohm University of Nuremberg*, who had developed these heating elements together since the turn of the millennium, received this outstanding award in November 2012 from *Martin Zeil*, Bavarian Minister of Economic Affairs, Infrastructure, Transport and Technology.

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