Product and System Innovation Based on Integrative Design with Ceramic (IDC): Joining Alternatives

Costs can be decreased by using a ceramic oriented design and by selection of the right manufacturing method. The process chain ends with a proper joining of the ceramic components. Joining of materials gives additional freedoms to the designer to reduce the complexity and size of the ceramic component resulting in higher strength (size effect) and reduced costs.

1 Introduction

Forty to thirty years ago advanced ceramic materials were developed for technical applications with improved properties in particular high strength for structural applications. This has given rise to visions like the “ceramic engine”. Despite many sound proposals for innovative ceramic applications the realization often failed due to a lack of production techniques, inadequate material properties, and poor knowledge in handling interface design in functional units with ceramic components. As outlined earlier [1], success of product innovation with advanced ceramics particularly requires consideration of the full process chain from powder to component.

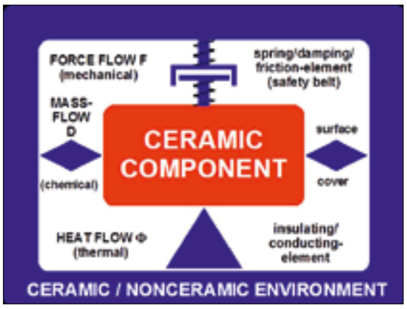

Fig. 1
Functional unit with a ceramic component [2]

Keywords
joining, brazing

Often design engineers frequently attempt to adopt a well-established design approach for a metal component to directly replace it with a ceramic component. This is because only advantages such as higher temperature stability, durability and better resistance against wear or chemical attack have been considered. This procedure is generally not recommendable and almost completely ignores the IDC approach. Quite apart from the fact that the component geometry is usually far away from being ceramic, loading and joining oriented, manufacturing and costs aspects were not considered. Costs of ceramic components depend on batch size (a first test component is very expensive) as well as on component size and complexity. These costs can be decreased by using a ceramic oriented design and by selection of the right manufacturing method. The process chain ends with a proper joining of the ceramic components.

Usually Ceramic components are usually integrated in functional units and interact with their environment by force-, heat-, and mass flow. Joining techniques give additional freedoms to the designer to reduce the complexity and size of the ceramic component resulting in higher strength (size effect) and reduced costs. Therefore this chapter of the series presents joining alternatives considering the interactions as presented in Fig. 1.

2 Joining oriented design

Joining techniques can be classified into the following categories: form-fit, force-fit and material-fit. The latter term applies to joints where the connection between the joint materials is ensured by atomic or molecular forces. Examples are adhesive, welded, soldered and brazed joints. Whereas force and form fits represent mechanical joints. Choosing the most appropriate joining technique is one discipline of the IDC concept [1] and has to be handled in the context of the different design phases. Each individual design phase is subjected to a bundle of interacting impact factors, and design measures and resultant interactions require accurate evaluation. Based on the joint requirements such as required structural strength (force flow), gas tightness (mass flow) and application temperature (heat flow) the concept definition has to consider material alternatives for ceramic and non-ceramic components (limit tensile stresses), processing

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alternatives (quality at the right location), and testing ability as well as cost aspects. In the IDC it is advantageous to begin with a pre-optimization of the tensile stress distribution due to operational loads assuming that the joint stresses are zero and there are no residual stresses. Tasks of the structural draft is in particular to limit the joining stresses at room temperature and service temperature and safe-guard high joint reliability at service temperature over the entire lifetime. Leaving gaps is encouraged to find the right compromise. Tailoring the heat flow can help to reduce joining stresses. The superposition of joining and loading stresses can reduce the total stresses and strains and require the use of Finite Element Analysis (FEA). Integration in a non-ceramic environment must not be seen just as a challenge, but also as a chance to use complementary features of metals or plastics for optimization. Plastic deformation of non-ceramic design elements reduces critical tensile stresses in the ceramic parts and act as load-limiters.

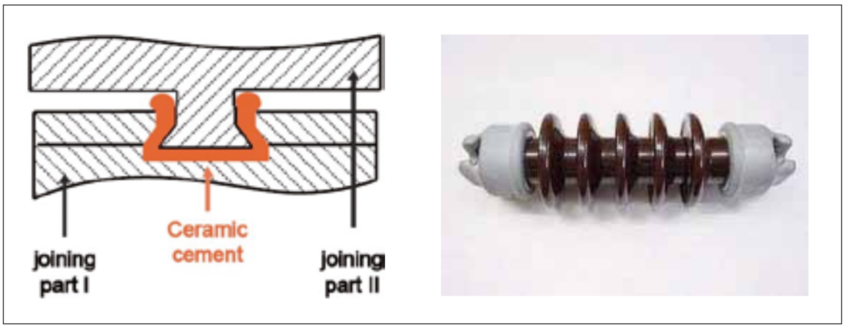


Fig. 2
Dove-tail joint of high voltage insulator (source: stehlitec.ch)

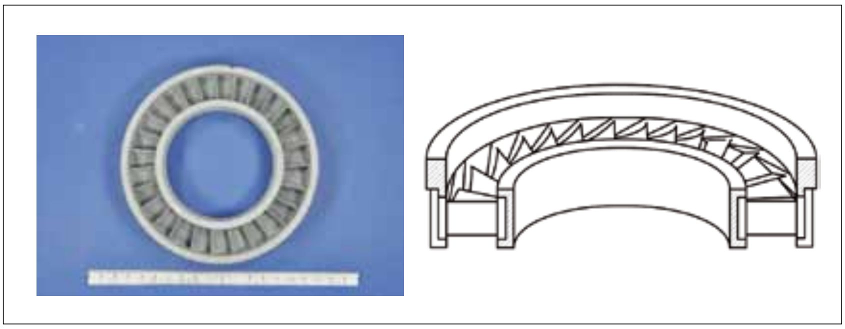


Fig. 3
Loose fit connection of paddles in a distributor

2.1 Form-fit

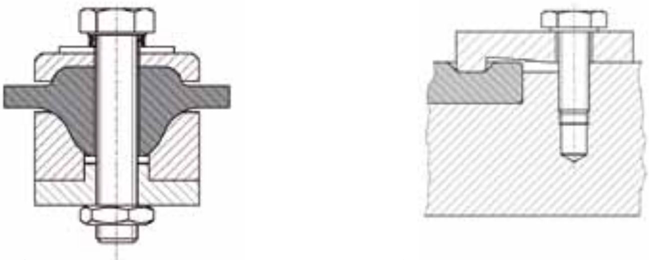
A classical form-fit is the cemented joint of a porcelain high-voltage insulator to a metal cap. The metal caps are intermediate elements for easy fixing of the insulator body to steel ropes. In service the insulator is exposed to tensile stresses. Although pure compressive loading is highly desirable because the compressive strength of ceramics is 10 to 30 times higher than their tensile strength it is technically not realistic. In service the insulator is exposed to tensile stresses and the applied joining technique has to ensure a non-critical superposition of loading and joining stresses. Fig. 2 shows a high voltage insulator with a dove-tail joint made with ceramic cement. Tensile loads on the metal cap are transformed into compression loads in the ceramic cement.

Fig. 3 shows a distributor for a gas turbine as an example for a form-fit with loose elements. Si_3N_4 paddles lie between an inner and an outer guide ring. They can adjust freely and no tensile joining stresses appear in the thin and complex paddles.

2.2 Force-fit

A major advantage of force-fits is that they are releasable connections. Main task in designing force-fits is to define the contact area at the right position (reduce bending). The contact area is typically subjected to the highest loads and has to be produced in the best possible quality. Considering the statistic distribution of flaws in ceramic components (size-effect) [3], a smaller contact area is preferred. It would be wrong to infer that a large contact area will always lead to reduced stresses. Geometric deviations such as unevenness or other imperfections as a result of inaccurate production or machining can result in 3-point bearing with unknown locations due the high stiffness of ceramic materials. This effect can be compensated by using ductile interlayers due to macro- and micro-deformations of the metal joint partner.

Screw connections are classical force-fits. Static friction avoids self-loosening of the screw. For joining ceramic components to ceramic or metal partners common metal screws can be used without special screw design. During tightening axial forces induce small elastic deformations in the screw and the work piece. Elastic



Con-rod/bolt:
- large force transmission area
- compressive loading
- spring elements to control thermal expansion

Overhung mounting with small axial hole

Fig. 4
Ceramic oriented screw fits (ceramic: grey) with controlled force flow [2]

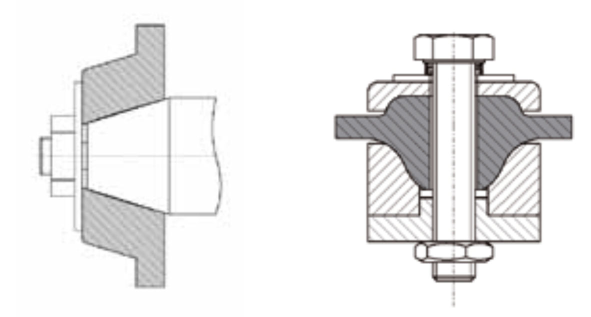


Fig. 5
Unfavourable metal in ceramic cone seat (left) compared to favourable ceramic in metal layout (right) [2]

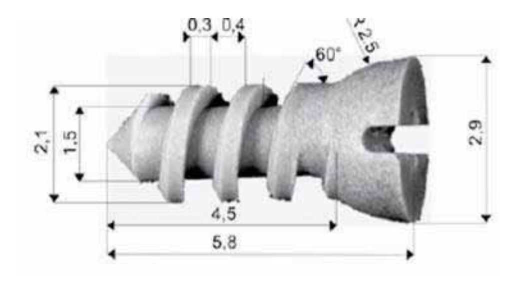


Fig. 6
Design of a zirconia screw for fixing bones [4]

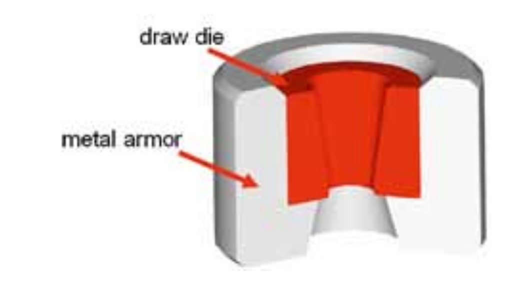


Fig. 7
Ceramic insert for deep drawing with metal armor

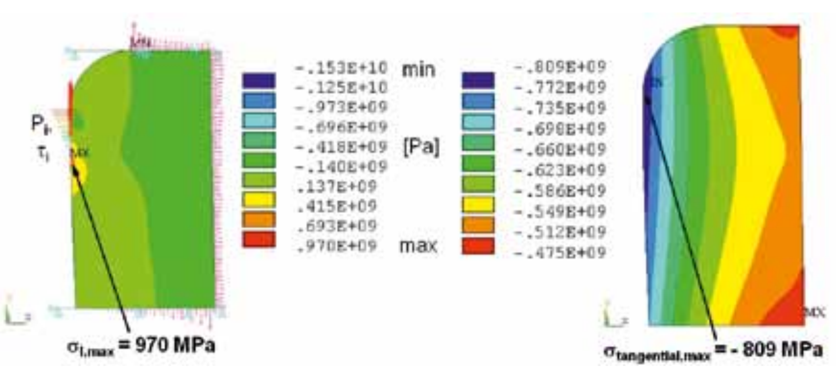


Fig. 8
First principle stress distribution from FEA in the ceramic die; right: superposition of working load (ejection stage) and joining stress (shrink fit), and just joining stresses

deformation of the joint partner acts like a spring as long as they will not be relieved by plastic deformation. The required elastic deformation cannot be delivered by the ceramic partner due to the high elastic modulus and the very small fracture strain. Thus the mating thread must be in the metal partner and a ductile washer should be used.

Considering displacement by thermal expansion is a particular task in the joint design. Joint materials most likely have different coefficients of thermal expansion (CTE) which often lead to overload of the ceramic component or in loss of fixing forces.

In a research project a ceramic “wood” screw was developed to secure ceramic osteosynthesis pads onto head bones, to be able to examine the brain though magnetic resonance tomography after an accident and an operation. FEA was employed to find a ceramic oriented design with minimized stresses in the ceramic screw, results are shown in Fig. 6.

For joining round ceramic components into a metal armor grouting and shrinking have to be proven to be highly reliable. In the former case, a cone seat and in the latter case a cylindrical hole and die have to be designed (Fig. 7). In both cases the oversize of the ceramic component defines the fixing force (friction) and therefore the resulting stress distribution. Ideal for the application is that the inner surface of the ceramic die has compressive joining stresses (Fig. 8). Superposition with loading stresses (tensile) during drawing of the metal work piece leads to small areas with critical tensile stresses. To reduce these local stresses the interaction of the work piece and the ceramic die has to be simulated for the drawing process. Employment of geometry optimization of the inner die allows to reduce the resulting tensile stresses.

In biomedical applications another well working example of IDC can be found. In a first view the joining technique for the artificial hip joint shown in Fig. 9 is unfavourable due to the aforementioned reasons (metal cone seat in a ceramic socket), but nonetheless it has proven to be the only reliable joining technique. The design must guarantee a fixed joint over the lifetime, and friction between the metal shaft and ceramic ball would result in toxic metal

Fig. 9
Cone seat of titanium shaft in alumina hip ball

Fig. 10
SiSiC construction elements by SCHUNK Ingenieurkeramik

grit. Material-fit using glues, see below, are also inacceptable from a medical view (no biocompatibility) and cannot provide the strength needed.

As a last point, an interesting application of form-fit was found at a German ceramic supplier. SCHUNK Ingenieurkeramik offers TRUSSCERAM, a building set ceramic beams with different connecting elements made of SiSiC. The ceramic beams can be assembled and screwed together to large structures. SCHUNK sees advantages in the low thermal expansion and the correlation of stability and weight. They underline that the “connecting elements are constructed to transfer the mechanical properties of the monolithic ceramic elements without any restrictions to the size or complexity of the structure” [5].

2.3 Material-fit

Material-fit covers different methods. Already in the Stone Age, people have joined ceramic parts before and during firing. Shaped unfired ceramic, the so-called “green body”, can be “glued” by using a slip of the same material. This method is well known in the pottery and is a perfect joining method for porcelain manufacturers. After drying, the joined components get fired to form a homogenous product. The joint is now characterized by the same material chemistry, but in general the dried slip shows a slightly higher porosity.

Joining of ceramic parts in the green stage was further developed for advanced ceramic materials. Without applying a slip between the joining parts, thin ceramic foils can be sintered under a moderate pressure to stacks. Before sintering, the single foils can be punched or coated by noble metals. Examples for applications are multilayer capacitors, chip carriers (Fig. 11) and plate heat exchangers. A welding method of sintered SiC plates to a plate heat exchanger without any detectable joining zone was presented by ESK/DE [6].

Of high interest for technical applications are joining methods for finished components of different materials. These methods can be distinguished between gluing (organic glues or ceramic cements), brazing with metal-braze-alloys, and brazing with glass-solders. NASA encountered some

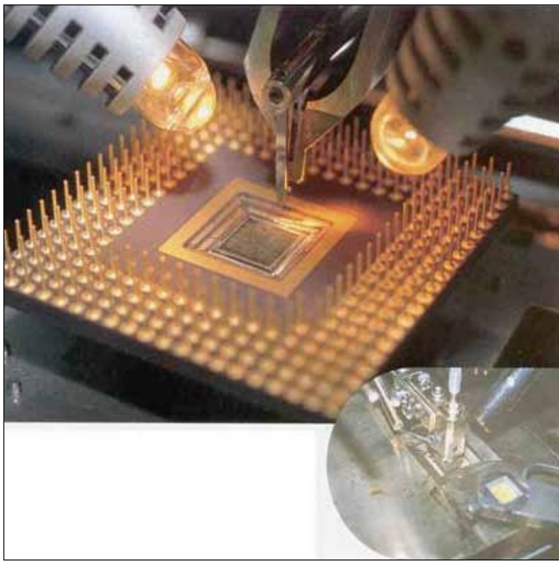


Fig. 11
Chip carrier as multilayer alumina foils with printed circuit paths

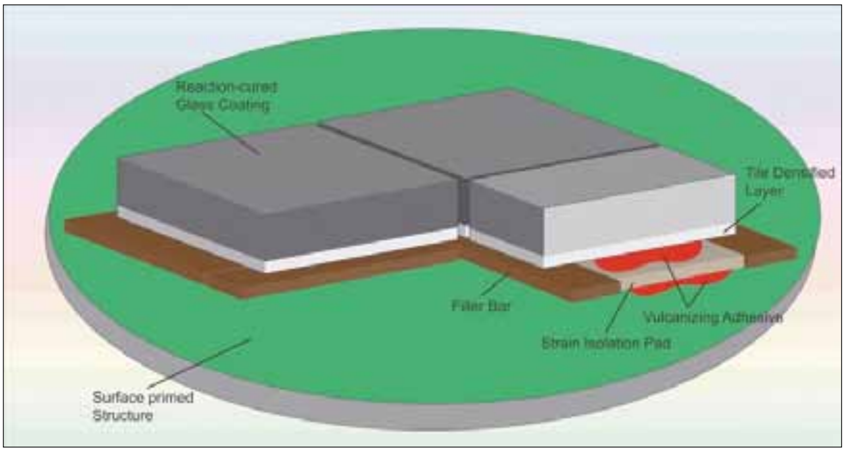


Fig. 12
Design of heat shielding tiles of the space shuttle, according to [7]

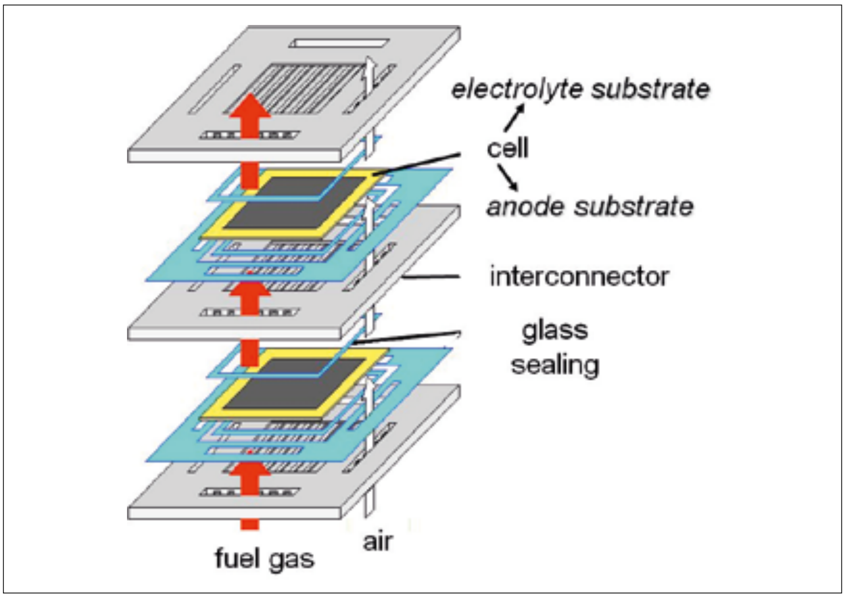


Fig. 13
SOFC planar design by Research Center Jülich/DE

problems in the beginning of their space shuttle projects with lost heat protection tiles. The solution, presented in Fig. 12, features a good example of IDC practice. Since the right combination of materials was found, the optimization of geometry and use of an interlayer to reduce thermal stresses, together with the improvement of the organic glue, resulted in a reliable system.

Another considerably complex example of joining different materials by material-fit can be found in SOFC technologies, where a gas-tightened electrically non-conductive sealing for working temperatures of around 700–800 °C is needed. Organic glues are not heat resistant and metal-braze alloys are electrically conducting. Glass solders could be a good choice but they have to be modified to higher CTE. Glass materials with a high CTE can be constituted but usually they exhibit low softening temperatures. Typically, glasses with high softening temperatures – which are needed for high temperature applications – show lower CTE. For SOFC applications, glass solders were developed with a CTE of $\alpha_{23–1000\,°C} = 10^{–10}$ K$^{–1}$ [8]. This CTE value fits best to the CTE of Y-doped Zirconia. In general, ceramics show a lower thermal expansion than metals. High temperature steels in particular show very high CTE values of about $\alpha = 16^{–10}$ K$^{–1}$ at 800 °C. To find a reliable joint for SOFC a special steel material with an adapted CTE of 11,8$^{–10}$ K$^{–1}$ at 800 °C was developed [9]. This example of IDC demonstrates that a design solution needs sometimes a special effort.

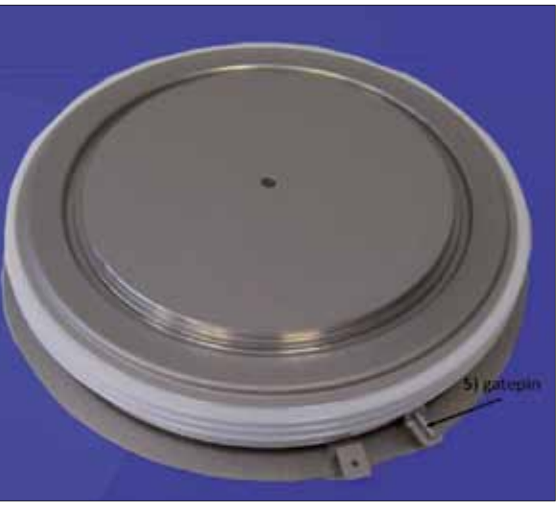


Fig. 14
Thyristor housing [9]

In most applications electrical isolation by the solder is not required, so brazing with a metallic brazing-alloy is possible. Due to the different atomic bonding of ceramics and metals, a wettability of ceramics with molten metal braze is difficult. The common way for brazing alumina ceramics is a preconditioning of the ceramic surface by a coating of MoMn under forming gas (N_2/H_2) at about 1400 °C, and an additional galvanic nickel-coating. By subsequent brazing at 800–900 °C the Ag/Cu braze alloy wets both joining partners and a gas tight joint with good strength is possible. An example for this 2-step brazing process is the thyristor housings in Fig. 14.

An alternative to this two-step process is "active brazing" in vacuum. Here the braze-alloys include active components such as titanium, which react with the ceramic surface during brazing. Those reactions decrease the interfacial energy and enable wettability [11]. In case of active brazing no pre-metallization is necessary. Fields of applications are cutting tools, electrical devices and insulators.

Both brazing processes need high vacuum or a protective gas atmosphere to prevent oxidation of the active component (e.g. titanium) or the metal partner. Some functional ceramics cannot be brazed in high vacuum due to thermodynamic instability. An example is the oxygen transport membrane (OTM) material $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}0_{3-\delta}$ (BSCF). For an application of this material as membranes in a membrane reactor, a joint to a high temperature steel of grade 1.4841 (X15CrNiSi25-21) is required. The dense $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}03\text{-}\delta$ ceramic exhibits oxygen permeability at temperatures of 800–900 °C and needs a gas tight joint, which is reliable at room temperature and also at an operating temperature of 850 °C. A new brazing alternative was developed by Weil et al. [12], called "reactive air brazing" (RAB). The brazing alloy is a silver-based braze with additions of copper oxide (CuO). CuO has a similar structure to the ceramic and reacts with the ceramic surface during the brazing process. The brazing process can be carried out in a regular electrical chamber furnace under air atmosphere [13]. The only problem is the oxidization of the metallic partner, which results in layers between braze and metal with an unacceptable porosity [14]. Because the necessity of a high vacuum process is omitted and the brazing process is cheaper, new applications are under development.

As described before, a mismatch of the CTE in the joining partners could become a critical factor for residual stresses. Thus, a simulation of the brazing process and the following application is eminently important for the design process. During brazing, stresses arise in the cooling phase depending on the mismatch in thermal shrinkage. The highest stresses can be expected at room temperature, by heating up again the joint to operation/application temperature, stress will decrease due to expansion and relaxation. This is an advantage as ceramic materials usually have a lower strength at higher temperatures.

The relevance of Finite Element Analysis (FEA) for the Integrative Design process and notably the joining process was described in more detail in the last issue of Ceramic Applications [15].

3 Joining in the Integrative Design process

Previously, oxygen membranes of dense $Ba_{0,5}Sr_{0,5}Co_{0,8}Fe_{0,2}O_{3-\delta}$ ceramic were mentioned which are the core of a module for oxygen separation from air, developed in a research project of the IWM [16]. At the beginning of our research activities, the membranes were manufactured as tubes by extrusion with two open ends. To avoid thermal stresses, the tubes should be fixed in a metal flange only on one side to allow unhindered expansion during heating and cooling. However, for this ceramic in oriented arrangement the loose end of the tube must be sealed gas-tight in advance. Closing the green ceramic with ceramic caps after extrusion was not successfully, but closing with metal caps by using reactive air brazing as joining method was applied successfully. Because the joining partners show very high values of CTE in the order of $16–18 \cdot 10^{-6}K^{-1}$, thermal expansion becomes a critical factor. The residual stresses during cooling down from brazing temperature (960 °C) to room temperature were calculated using FEA. Within these simulations the geometry of the cap and the joint were optimized and as a result the stresses in the ceramic could be reduced [16]. In the first design, the metal cap overlaps the tube wall inside the tube, whereas in the second design the cap overlaps outside. These results in an inner braze meniscus and an outer one, respectively. In the first case the simulated stresses are about 120–155 MPa, in the second case just in the range of 40–80 MPa. A complete new design with cap-to-tube sleeve joint resulted in a not-gas-tight joint, and the calculated stresses were higher than before.

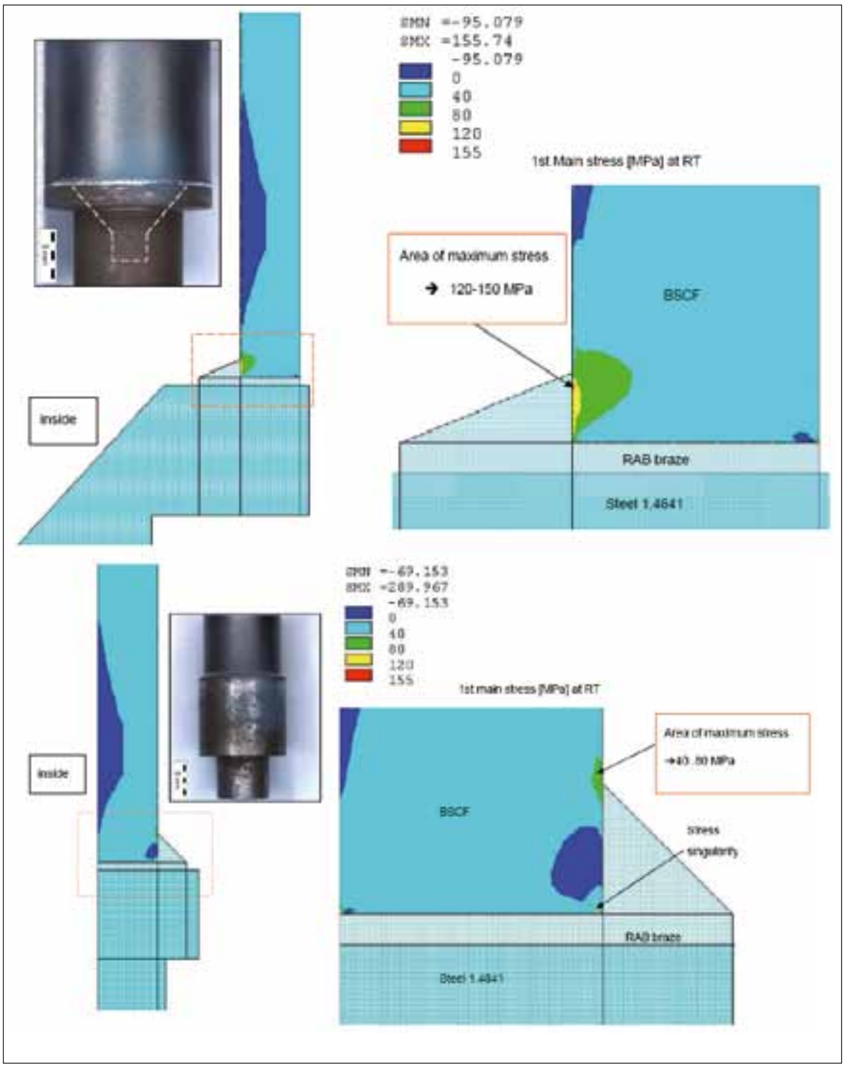


Fig. 15
FEM-simulation of joining stresses with braze meniscus inside (above) and outside (below) [17]

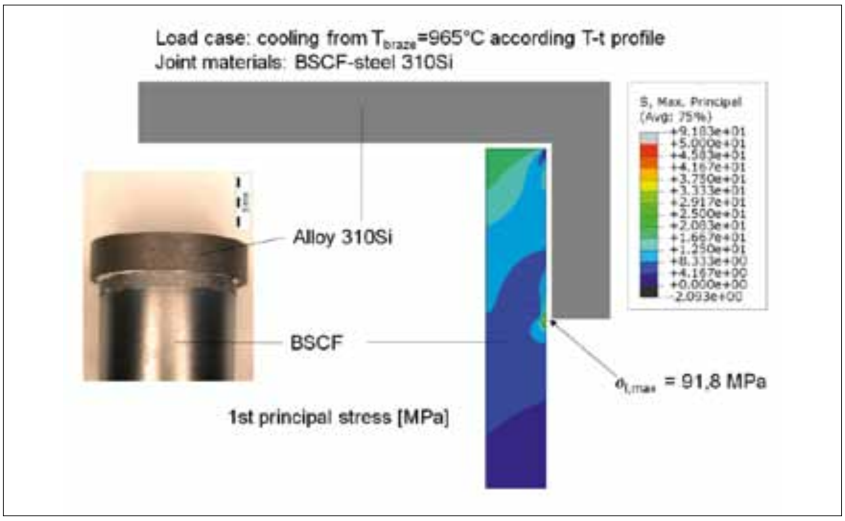


Fig. 16
Simulation of cap-to-tube sleeve joint [17]

Fig. 17
Segmented auger with SSiC elements and a ZrO_2 front element compared to the original steel auger [18]

In a loop of our IDC process, use of brazing was reconsidered and IWM developed a manufacturing process for the ceramic tubes using cold isostatic pressing. With this process it is now possible to manufacture tubes with one closed end directly in the shaping process. Such tubes have to be joined at the open end only. In an adapted design of the membrane process this end can be cooled so that gluing became a possible alternative.

Another good example of Integrative Design with ceramics can be found in a cooperative research project at IWM some years ago. The BMBF founded project “Ceramic Components for Processing Heavy Abrading Compounds” developed ceramic components for wear loaded extrusion and injection moulding processes. The cooperation structure of project partners involved a ceramic supplier (H.C. Starck GmbH & Co. KG), a supplier of extrusion machines (ECT-Kema GmbH), an end-user (Hermsdorf Institute for Technical Ceramics – HITK) and IWM (at the time: Institute for Ceramic Components in Mechanical Engineering). Within the ICD design process the proper materials and manufacturing processes had to be defined. Furthermore suitable module- and joining technique was needed [18]. For finding the optimal geometry of the ceramic auger it was first necessary to determine mechanical, thermal and chemical strain during usage. Thus the construction was supported by FEA simulations to calculate the fracture probability of the ceramic components. An optimized auger design should fulfil following demands [17]:

- Auger segments instead of a monolithic design enabling the optimum material in each specific zone
- Zones of high wear need hard metals or ceramic
- Suitable connection system for a safe transmission of the different torsional strains between auger segments and shaft
- Solution for centering especially long augers
- Possibility of tempering the auger (cooling or heating)
- Acceptable cost performance.

Regarding Fig. 1, the force-, heat- and mass flow were taken into account for selecting the right materials at the right location. The extruded mass in the extrusion process contains thermal sensitive organic additives and has to be cooled. Therefore silicon carbide was chosen as ceramic material for the auger, due to its acceptable thermal conductivity ($\lambda = 130$ W/m · K). At the front of the auger, high stresses occur and a material with high strength is required, such as zirconia ($\sigma_{4pb} > 1000$ MPa). Because this area is very small, the low thermal conductivity of ZrO_2 ($\lambda = 2,5$ W/m · K) can be neglected at this location. Fig. 17 shows that the IDC design process has considered the maximum producible length of the ceramic. The green shaping process was the limiting factor, and two SSiC elements were joined with a front element of ZrO_2 and retention of the metallic force transmission.

The selection of the joining technique respects the low temperature of the application and allows for a cost-conscious gluing method. To guarantee a reliable torque loading, the elements are glued onto a metal shaft, see Fig. 18. This concurrently guarantees the linear alignment of the elements.

4 Summary

Joining is an important part of IDC. As described in former issues of our series the mechanical reliability of ceramic components depends on local stresses linked to the material quality at this location. The critical stress must be seen as a superpositioning of application loads and residual stresses. Correct joining offer an opportunity to reduce stresses (compression stress by joining) and can enable quality at the right location. Using simulation tools like FEA, stress distributions can be calculated, first considering the joining process and subsequently the application. In iterative loops the design of the components and of the joints can be optimized so that stresses at critical locations and at critical operating conditions will be reduced.

The IDC process does not end with reliable working ceramic components and functional units but must also aim at economic success. Manufacturing small ceramic elements with high reproducible and testable quality to acceptable costs in combination with the right joining technique is a key for success.

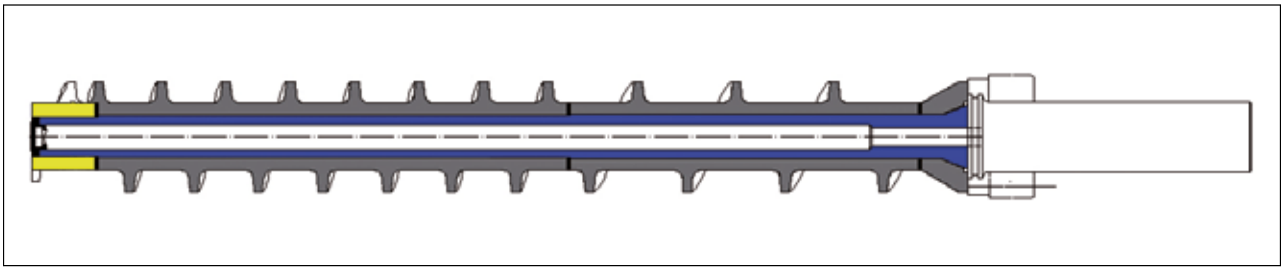


Fig. 18
Cross section of the joint elements

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