Product and System Innovation Based on Integrative Design with Ceramic

The paper is presenting a briefing on integrative design with ceramic (IDC) and gives product and system examples that are graded as valuable, to be reported in detail in following issues of CERAMIC APPLICATIONS.

1 Introduction

A sound knowledge about the ongoing development of materials based on metals, plastics and ceramics as well as of their compounds has always been and will also be in future of key importance for product and system innovation, but not only on its own. History has shown in good and bad ways how important it is to interlink all elements of the development chain computer aided in a most efficient way, in order to assure product or system reliability economically. Design is thought to be responsible for keeping the information flowing between all experts involved, independently of their location.

In the seventies and eighties it was dreamed of a "ceramic engine" for personal cars or about ceramic gas turbines. At the same time the books for the application fields of bio ceramic und ceramic multilayer housings have been opened. This was the start of a huge long term learning curve in, how to cope with the risks und how to get access to the advantages of ceramics. Today it is known that the dreams concerning car engines have not been realized in full, but essential spin-offs are in use. Nowadays no car is running without ceramic components operating in the shadow: mechanical seals in water pumps, catalytic carriers, diesel soot filters and multilayer housings for engine management. High demanding examples are ceramic brakes, stopping cars and trains more safely at shorter distances and ceramic roller bearings, improving the performance in racing cars and making fuel pumps working in space shuttles. Future dreams of electrical driven cars are linked to oxide fuel cells with ceramic electrolytes and electrodes. Ceramic joints for hip and knee, mostly sliding on polyethylene caps, are now meeting the highest standards.

Developers in innovative companies are getting increasingly aware of the advantages of ceramic materials e.g. high temperature strength and shape stability as well as chemical resistance, extreme hardness and wear resistance. But often they need support to use these materials successfully as they have not the knowledge needed about the specific behavior of ceramic materials. Mostly, it is not possible to change a metal component by a ceramic one without changes in design and joining technology. Material oriented designing is an important factor for successful applications of ceramics.

Keywords
integrative design,
joining,
design rules

2 Orientation properties of selected ceramics

This chapter is concentrating on thermo-mechanical properties with some advices for non-insiders how to use them.

Ceramic components are mainly manufactured by a powder process comparable to the powder metallurgy. After compacting the powder in a die, by slip casting or by powder injection molding a sintering process is needed. Ceramic components can be manufactured with high density and improved strength for hip joints or with high porosity and low strength for filters. Properties depend not only on the chemical bonding of the atoms. Particularly, the mechanical properties like the strength, which is notably in focus of mechanical engineers, depend on the microstructure and residual stresses due to manufacturing.

Ceramic cannot absorb energy by plastic deformation and will crush if the stress at a fault in the microstructure exceeds a critical stress σ_c. This depends on the size of the flaw a and is described according to fracture mechanics for short time strength in equation 1.

$$\sigma_c == \frac{K_{Ic}}{\sqrt{a_c * Y}} \quad (1)$$

K_{Ic} is the stress intensity factor (fracture toughness), Y is a geometry factor de-

Dr. Ewald Pfaff,
Prof. em. Horst R. Maier
Institute for Materials Applications in Mechanical Engineering (IWM)
RWTH Aachen University
52062 Aachen
Germany
www.iwm.rwth-aachen.de

Corresponding author: E. Pfaff
e.pfaff@iwm.rwth-aachen.de

pending on size of flaw to sample, a_c is the critical size of a penny shaped sharp flaw (vertical to tensile stress). Statistical scattering of a_c results in scattering of the critical stress σ_c and defines the Weibull parameter m in Tab. 1.

σ_b in Tab. 1 represents the mean value of a series of n standardized bending tests on rectangular samples. Only after fracture the size of a_c can be estimated (principle of proof testing).

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_2}{V_1}\right)^{\frac{1}{m}} \tag{2}$$

A larger component will fail statistically at lower stresses than smaller ones. This phenomenon is called "size effect" and is presented in the equations 2 and 3. The volume of component 1 respectively 2 is loaded with uniform tensile stress σ_1 respectively σ_2. m is the Weibull Modulus of the material, a rate of scattering of the flaw sizes due to manufacturing.

The tabled strength data of ceramic materials cannot be directly used to predict the failure probability F_B of a ceramic component. A detailed FEA stress distribution in the component considering the external loads and the residual stresses is needed. Then the failure probability can be calculated using equation 3. In addition to short time behavior of ceramics for lifetime consideration, subcritical crack growth has to be considered depending on load and environment conditions e.g. humidity. To include this behavior in reliability analysis additional material parameters can be tested and used in special equations.

$$F_B = 1 - \exp\left[-\frac{1}{V_0}\int\left(\frac{\sigma_t(x,y,z)}{\sigma_{OV}}\right)^{m_V} dV\right] \tag{3}$$

Because of the statistically fracture behavior of ceramic materials special application oriented tests should check the calculations. In special cases like artificial hip joints a proof test can be used to guarantee the reliability for a patient's or machine's life.

Macroscopically monolithic ceramic materials show at room temperature a linear elastic behavior till fracture (Fig. 1). This abrupt fracture can be seen as a disadvantage but in return the form stability at high temperature is also an advantage of ceramics. On the other hand the low elastic modulus and the high plastic deformation of metals and especially plastics can be used in joints and system units to compensate the low deformability of ceramics and local stresses.

In Figs. 2–6 some component applications of the tabled ceramic materials are presented.

Tab. 1 Orientation data of selected ceramics at room temperature ([1]) GPSN with improved thermal conductivity)

Material	Producer [source]	σ_b [MPa]	m	K_{Ic} [MPa√m]	E [GPa]	α (RT–1000 °C) [$10^{-1}K^{-1}$]	λ [W/m·K]	ρ [g/cm³]
Al_2O_3 (99,8 %)	Ceramtec	630	15	4,3	406	8,5	30	3,96
Al_2O_3 (96,0 %)	Ceramtec	310	13	4,0	350	8,8	20	3,75
ZrO_2 (3Y)	Ceramtec	1050	>10	6,5	210	11,7	2,5	6,05
SiC (SiSiC)	Ceramtec	340	8	4,0	380	4,9	120	3,07
SiC (SSiC)	ESK	510	10	4	430	4,5	130	3,16
Si_3N_4 (GPSN)	FCT	750	>14	7,5	290	3,2	23	3,25
Si_3N_4 (GPSN)[1)]	FCT	780	>14	7,5	300	3,2	85	3,26
Si_3N_4 (HPSN)	FCT	1100	>14	7	310	3,2	65	3,27

Advices and explanation concerning Tab. 1.

Properties of ceramics are depending on microstructure and therefore they are linked to processing route and will vary from manufacturer to manufacturer and from component to component.

Values of strength are measured on small samples which are perfectly ground and polished and are not directly comparable to real components. Manufacturer or literature delivers tabulated material data characterized by the chemical composition only. It is not possible to use these data for a final designing of a ceramic component but for a first orientation only. As a conclusion application oriented sampling and testing should follow as soon as possible within the design chain.

Actual data of selected ceramic materials at room temperature are given by ceramic producers in Germany and are listed in Tab. 1.

Don't compare directly the mean values of 4-point bending strength σ_b of ceramics with tensile strength σ_t of steel due to size and stress distribution effects mentioned before.

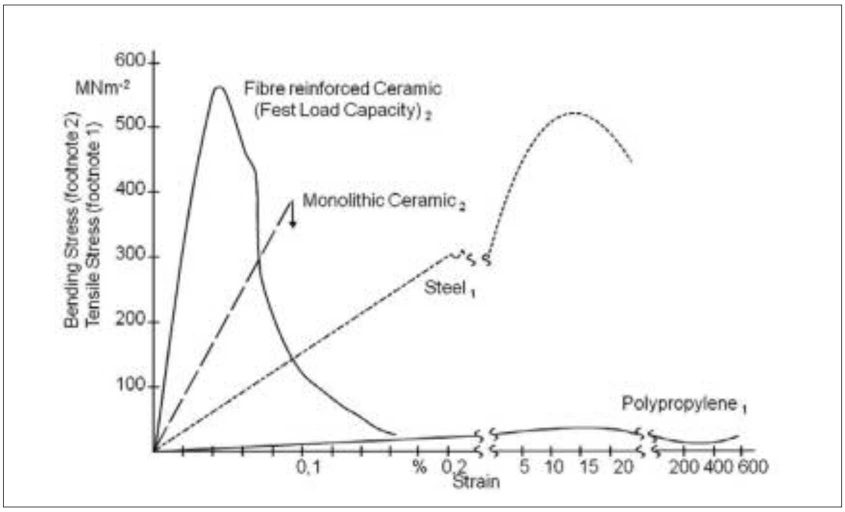

Fig. 1
Stress-strain behavior of different material groups

Fig. 2
SiSiC-Fan (Schunk, Germany)

Fig. 3
ZrO_2-spring (Fraunhofer IKTS) [1]

Fig. 4
Si_3N_4-Housing of a infrared camera (FCT, Germany) [2]

Fig. 5
Bearing with Si_3N_4-rollers, design and final finishing by Cerobear (Germany)

Fig. 6
Implants based on Al_2O_3-ceramics (Ceramtec GmbH, Germany)

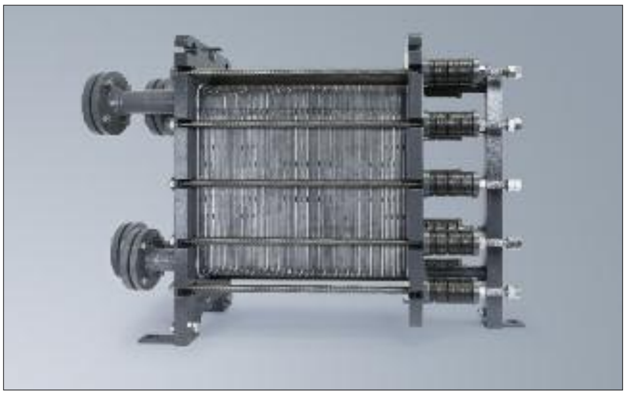

Fig. 7
SiC-plate heat reactor (ESK, Germany) [3]

Remark from the editor:
More details on ceramic roller bearings (Fig. 5) and SiC-micro reactors (Fig. 7) you can find on
page 10: „Roller Bearing Technology for the Highest Demands“ and
page 26: „Fully Welded Ceramic Components for High Performance Heat Exchangers and Flow Reactors.“

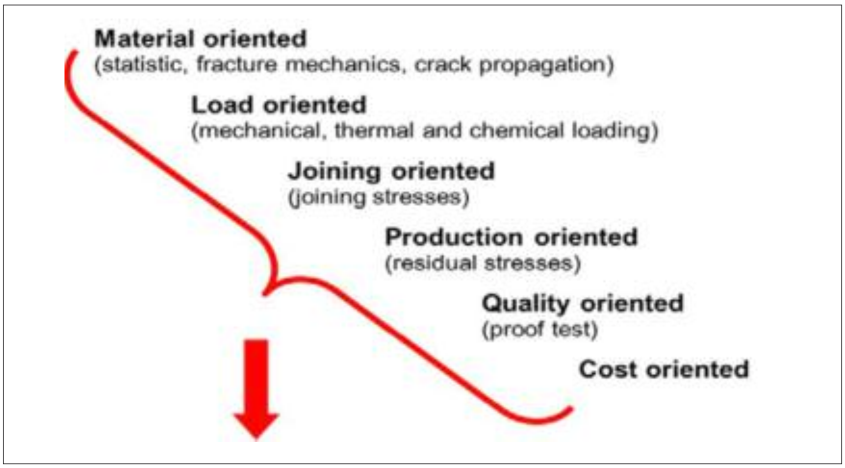

Fig. 8 Integrative design with ceramic [5]

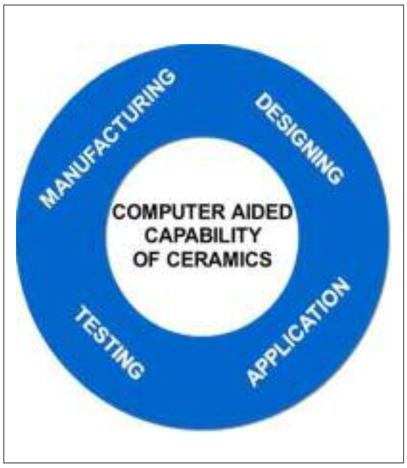

Fig. 9 Basic expertise elements [4, 5]

3 Integrative design with ceramic (IDC)

Definition and features are founded in [4] and include the syntheses of loading, joining and residual stresses, depending on aspects of materials, loading, joining, manufacturing, quality assurance and costs. A corresponding presentation is given in [5] and a short version in [6]. Some excerpts are given below.

Integrative designing with ceramic is aiming for the carry on development of an iterative optimization strategy that can cope with computer aided results and empirical insights in combination. For further improvement of the optimization strategy it should be kept in mind. Computer aided stress analysis is highly advanced in the fields of loading and joining. In the field of manufacturing the empirical insight is still dominating and therefore has to be covered by other means, e.g. by proof testing methods.

The support by IDC so far does:

- Intensive the application oriented dialog between people in design, joining and manufacturing
- Invite to create suitable metal and/or plastic surroundings
- Make clear the necessity to match the joining individually to the application
- Enable to benefit from residual stresses (blessing, knowledge of σ_l and σ_j)
- Explain failure by residual stresses (curse, lack of knowledge of σ_l and σ_j)
- Force to put the required quality at the right location
- Use low stresses areas for economical production
- Activate the intuitive generation of methods for design optimization
- Provide the basis for further development in integrative design with stronger link to computer-aided design optimization.

3.1 Some general features

The definition and major features of IDC are illustrated in Fig. 8. The basic expertise elements in Fig. 9 should be identical in education, research and praxis, (especially for the interaction between suppliers, manufacturers and users). If one element is defined "integrative" in consequence the total approach is condemned to. So, the term "application" is part of this integrative approach as well. The so called "Design Management" with its design phases and major impacts in Fig. 10 does indicate the necessity of objective-concept- and draft-matching (often in repetition or in parallel alternatives) prior to computer aided design. The scheme of a functional unit (system) is shown in Fig. 11. The ceramic component is linked to the environment by force-, heat- and mass-flow in interaction. So suitable joining is a very demanding task. The

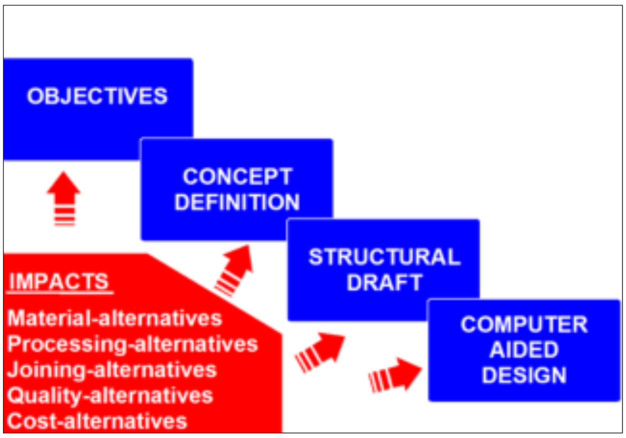

Fig. 10 Design phases [4, 5]

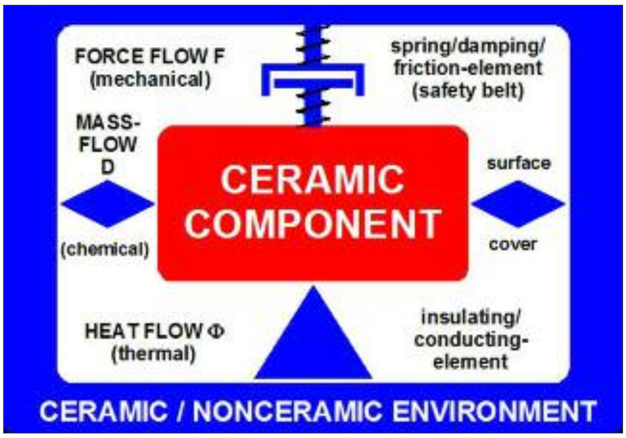

Fig. 11 Functional unit with a ceramic component [4, 5]

Fig. 12 Computer aided component capability [4, 5]

term of "non-ceramic environment" is inviting to use the complementary features of metals, plastics, compounds or any other media (solid, liquid or gas) for optimization. The computer aided component capability illustrated in Fig. 12 is leading to the maxim "quality to the right location."

3.2 Some selected design guidelines

It is important to stress the point that due to the lack of accurate forecast of loading profiles and the limited quantification of component features and residual stresses, the pure computer-aided reliability forecast is limited and there for the designing and performing of application oriented proof tests will remain a dominant task for the near future. In this context only some empirical insights are illustrated or listed below. It has to be kept in mind that joining is an essential part of designing and it needs its own manufacturing expertise in order to bridge ceramic with ceramic or non-ceramic components. There for the fruits of general design rules are limited.
Examples of material and joining oriented design are given in Fig. 13.

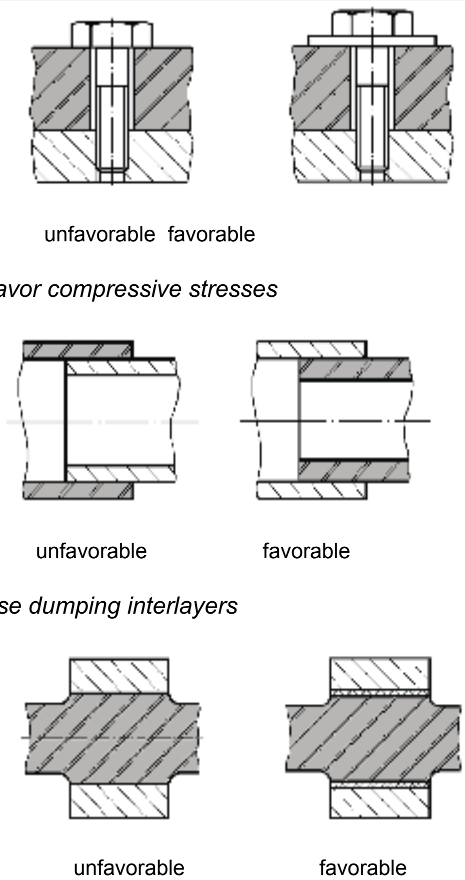

Fig. 13 Joining oriented design

3.3 Fundamental design rules

- Ceramic should be stressed by compression as the compression strength is 10 to 30 times higher than tensile or shear strength
- Compression load means not automatically compression stress e.g. an eccentric loaded round bar creates tensile stresses too, due to bending. Another example is a tube or a negative curved tube with outer pressure loading
- Compression load must be secured over the sighted live time, also during temperature changes
- Tensile strength decreases with component size and complexity. Aim for Modules with limited size and with homogeneous microstructure
- Limited ductility and high Young Modulus require
  – avoiding sharp changeover
  – avoiding wrong loads based on tolerance deviations
- Impact sensitivity requires
  – rounded edges
  – spring or damping elements
- Reducing thermal stresses
  – heat insulation by intermediate layers or air spaces
- Intensive use of the high contact strength
  – contact area as small as needed and located reproducible at defined positions.

For applying general fundamental design rules knowledge about loading is a must. This is illustrated in Fig. 14.

The IDC approach has been developed over years as an "Innovation Chain Ceramics" at RWTH Aachen University, guided by the Institute for Ceramic Components in Mechanical Engineering (IKKM), founded in 1987 and the affiliated Institute for Pro-

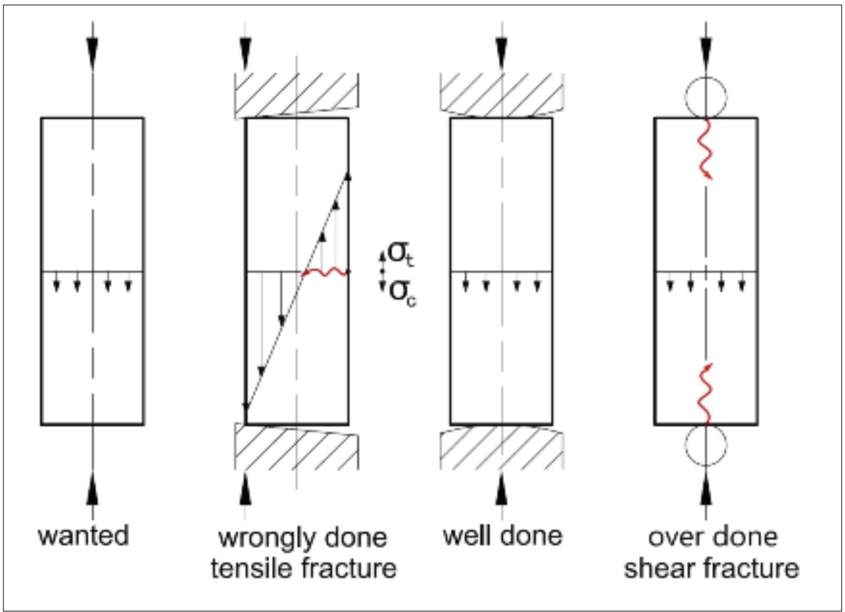

Fig. 14 Tensile and shear failure due to compression load

cessing and Application of Ceramic at the RWTH Aachen University (IPAK).

3.4 Changes in the fundamental attitude

- Ceramics are not only "brittle", but show limited ductility and therefore "dimensional stability" up to fracture
- The "fracture mechanics engineer" concerning specimens (and components) is followed by the "reliability and economy analyst" of functional units and systems solutions ("successful marriage of materials")
- Reliability and costs are no "obstacle" but a "challenge"
- "Euphoric hopes" give way for "realistic expectations"
- Strengthening of joined efforts with early use of spin-off-effects.

IDC has been applied so far mainly for hybrid systems of ceramic-metal and for some of ceramic-plastic and ceramic-bone as well. Every new application case will be used for further optimization.

4 Examples of product innovation projects based on IDC

Some essential projects of IKKM are listed and briefed below:

1) Design and testing of a prototype SiSiC heat exchanger for coal combustion [7]

This project with scientific and industrial partners shows extreme large dimensions of SiSiC-modules piled up to system length of some meters. The initial force and heat flow has been changed basically in order to reduce the risk of different thermal expansion involved. The chemical attack has been taken into account as well, using application oriented testing.

2) Silicon Nitride as biomaterial [8]

This project with hospital partners did concentrate on the bio compatibility of highly dense silicon nitride in comparison to the established bio ceramic candidates alumina oxide and zircon oxide with the outcome: High strength silicon nitride components can be taken into account for bio mechanical applications.

3) Reliability of ceramic multilayer capacitors [9]

This project with a scientific partner at the RWTH Aachen University is concerned with functional ceramic components of extreme small sizes of millimetres with thicknesses clear below millimetre. It is a leading example for simulation and testing of very complex linked superposition of load, joining and residual stresses. The joining of industrial produced multilayer modules has been done by means of a mass production brazing process.

4) Design of ceramic screw conveyor parts for extrusion and injection moulding [10]

This project has shown that IDC can successfully bridge complex tasks between manufacturing and applying industry. Different ceramics like silicon carbide and zircon oxide had to be selected depending on local application requirements suitable shaping of ceramic components in context with the aimed for metal-ceramic hybrid system had to be performed including the demands for joining. The dimensions of the ceramic components are of some 10 mm, the system shows a length towards 1 m. Testing has been done in original industrial equipment and did show clear advantages concerning reduced wear of components and improved quality of the media transported.

5) Porous ceramic components for immobilization of microorganism in a bioreactor [11]

This dissertation is used as an eye opener for using open porous structural ceramics for innovative applications in combination of classical structural with new functional tasks. The main points have been, how to invite microorganism to settle in a special build equipment of standard honeycomb components and how to quantify this immobilisation.

In 2006 *IKKM* (ceramic based) was merged with the Institute of materials science *(metal based) to the Institute of Materials Applications in Mechanical Engineering IWM*. This is an essential mile stone. Seen from the ceramic side the in house gain in expertise on metal knowledge and experience will increase basically the capability in high complex systems with joint metal and ceramic components.

This marriage of material knowledge is supporting a key project of IWM, OXYCOAL-AC [12]. Here a high temperature membrane module for oxygen generation has been designed [13] including developing the process route for an in house manufacturing of the ceramic membranes in a pilot production and quality assurance. Therefore a sound knowledge of the behavior of a new ceramic materials group (MIEC perovskites) as well as of high temperature steel or alloys are necessary for the integrative design concept. For this application also the creep behavior of the ceramic material has to be taken under consideration and the established know-how from the metal side is very helpful. A special challenge is the joining technique for a gastight ceramic-metal joint operating at 850 °C and gas pressure difference of up to 20 bar. Emphasis is put on a new brazing technology in air the so called reactive air brazing [14]. This complex research project is an excellent example of IDC and will be described in following issues in detail.

A just started new cooperation project with *Siemens AG* (Fossil Power Generation Division) is using the IDC approach for developing new ceramic liners for gas turbines. Here the IDC approach will be transferred to refractory materials.

Acknowledgement

The presented integrative approach has been improved and will further improve with every project and its people involved. We take this opportunity to say thank you to all partners and colleagues.

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