FE-Simulation (FEA) for the Designing of Ceramic/Metal Assemblies – the End of Trial and Error?

With the FEA as a part of the integrative design process it is possible to precisely calculate the stresses, which are induced in ceramic components during the assembly or operation. By using postprocessors short-term and also long-term fracture probabilities can be calculated. The precision of the results depends highly on the used input data and the introduced model simplifications.

Introduction

The finite element analysis (FEA) is used in process- and component simulation for the design of ceramic components. Especially in the field of technical ceramics, which follows different materials laws than for example steel, this method is not wide spread yet. To determine the reliability of highly stressed components, which try to exploit the limits of the construction material, sophisticated and expensive screening- and development tests have to be conducted. The final component design evolves through multiple iteration cycles. The amount of iteration cycles can be reduced by the experience of senior ceramic design engineers. The evaluation of the chosen design however can only be subjective by means of the resulting component during operation. This evaluation of ceramic/metal assemblies will be complicated by complex geometries and the variety of applied materials. By use of FEA different possible design proposals can be objectively compared to each other on the basis of predefined criteria. So the best possible starting design can be chosen. The FEA can be seen as part of the integrative design process of ceramic components [1, 2]. This process can be either applied to the new construction or the re-evaluation of existing designs and processes to assess necessary rationalization measures to increase efficiency.

Using the example of a thyristor housing, manufactured by *LAPP Insulators Alumina GmbH,* the possibilities which arise from the use of FEA shall be pointed out. For this purpose the assembly of a thyristor for high currents, as well as the necessary fundamentals of numerical component design and the required specific material properties are presented. Following this, numerical design calculations for selected examples are pointed out and the results are discussed. Finally, potential limitations that have to be considered when using FEA for the designing of ceramic components will be discussed briefly.

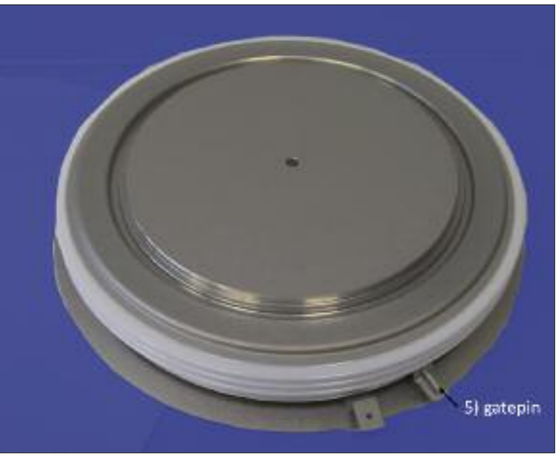

Fig. 1
Thyristor housing

Keywords
finite element analysis (FEA),
ceramic/metal assemblies,
thyristor housings

The thyristor

A key component for nowadays power transmission grids is the thyristor (Fig. 1). With this component electrical power of up to 10 GW can be switched by using small control currents. The thyristor addressed in this paper is made up from four different materials, which are joined together to a complex unit by brazing.

The thyristor consist of the following components (Fig. 2):

1. insulator-housing of Al_2O_3,
2. upper and lower contact piece of OF-copper,
3. membrane of OF-copper,
4. flange of OF-copper,
5. gate pin of NiFe42,
6. semiconducting package (molybdenum package and chip).

The insulator housing made of Al_2O_3 is metallized where the ceramic is to be brazed to the membrane, the flange and

Dr. Kai Sauerzapfe,
Dr. Holger Wampers
LAPP Insulators Alumina GmbH
96257 Redwitz
Germany
www.lappinsulators.com/alumina
ksauerzapfe@lappinsulators.com

the gate pin. Since a passive brazing technique will be used, the metallization is needed to ensure the wetting of the ceramic by the braze. A MoMn paste is used for the metallizing layer, which is burned in in a reducing atmosphere at a temperature of 1400 °C. Finally the metallizing layer will be nickel plated. The layer thickness is 5–18 µm for the MoMn and additionally 2–4 µm for the nickel layer. The membrane and the flange are brazed to the ceramic via blade joint (Fig. 3). The gate pin will be braced by circumference joint in the same brazing process.

An AgCu braze with a processing temperature of 820 °C is used. Every metallic component of the thyristor housing is nickel plated afterwards to prevent oxidation. After the brazing process the braze joints are vacuum tight up to 10^{-9} mbar l/s. After integration of the semiconducting package in the housing by the customer the flange will be cold welded with another membrane and contact piece.

Numerical component design by FEA

The numerical component design of ceramic components is based on the simplest form of the weakest link model. The calculation of the short-term fracture probability is carried out by means of the 2 parameter *Weibull* approach. The approach is described by eq. 1 provided that statistically distributed flaws in the volume are the reason for component failure:

$$F_V(\sigma) = 1 - \exp\left(\frac{-1}{V_0}\int\left(\frac{\sigma(x,y,z)}{\sigma_{0V}}\right)^m dV\right) \quad (1)$$

By introduction of the peak stress σ_p (eq. 2) and the effective volume V_{eff} (eq. 3) eq. 1 can be simplified for further use (eq. 4).

$$\sigma(x,y,z) = \sigma_p f(x,y,z) \quad (2)$$

$$V_{eff} = \int_V f(x,y,z)^m dV \quad (3)$$

$$F_V = 1 - \exp\left(\frac{-V_{eff}}{V_0}\left(\frac{\sigma_p}{\sigma_{0V}}\right)^m\right) \quad (4)$$

Eq. 3 for the calculation of the effective volume can be solved analytically for simple geometries. In case of complex geometries and stress singularities the FEA has to be used. Here an element fracture probability for every discretizing element using eq. 4 will be calculated. The component fracture probability will be attained by independent superposition of the element fracture probabilities (eq. 5). This is done by a separate post processor.

$$F_{ges} = 1 - \left[\prod_{i=1}^{n}(1 - F_i)\right] \quad (5)$$

The usage of the post processor enables the evaluation of the calculated stresses by calculation of the short-term fracture probability. In contrary to metallic materials where the *von-Mises* stress is used for the evaluation, a stochastic approach as described above by the Weibull equation is used to assess ceramic components by the short-term fracture probability F.

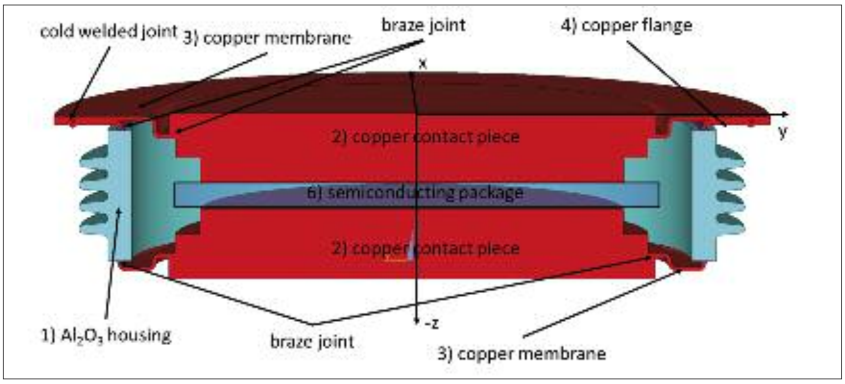

Fig. 2
Assembly of the thyristor

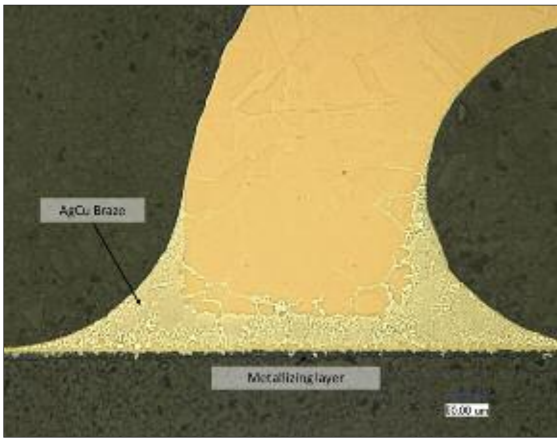

Fig. 3
Blade joint of an Cu-membrane ans Al_2O_3 thyristor housing

Material properties

Based on the following material properties (Tab. 1) the numerical calculations were done. Listed is just an excerpt of the used material properties. For the numerical calculation temperature dependent properties were used.

Tab. 1
Material properties

	Al_2O_3	OF-copper (Soft-annealed)	AgCu780
Coefficient of thermal expansion [10^{-6}/K] (20–500 °C)	7,8	18,2	19,8
Young's modulus [GPa]	380	115	98
Yield point [MPa]	–	120	112
Tangent modulus [GPa]	–	6	5
Density [g/cm³]	3,92	3,92	10,5
Poisson number [–]	0,22	0,31	0,34
Specific heat capacity [J/kg · K]	850	385	235
Thermal conductivity [W/m · K]	20	430	400
Weibull modulus [–]	15,95	–	–
Characteristic strength [MPa]	356,6	–	–

Tab. 2
Results of the FEA, joining stresses

Load Case	F_{ges} [%]	V_{eff} [mm³]	$\sigma_{I,max}$ [MPa]	$\sigma_{v.M,braze}$ [MPa]	$\varepsilon_{plast,braze}$ [%]	$\sigma_{vM,copper}$ [MPa]
Contact piece ideal concentric ally aligned, braze thickness 100 µm	0,056	20,07	184,8	631	10	458
Contact piece ideal concentrically aligned, braze thickness 80 µm	0,061	19,44	186,2	602	9,5	449
Contact piece ideal concentrically aligned, braze thickness 120 µm	0,054	20,3	184,3	672	10,8	447
Lower contact piece +0,5 µm and upper contact piece –0,5 µm shifted out of the center in x-direction, braze thickness 100 µm	0,088	7,74	201,9	631	10,1	447
Lower contact piece 0,5 mm shifted in y-direction, upper contact piece 0,5 mm shifted in x-direction, braze thickness 100 µm	0,089	7,75	201,9	631	10,1	447

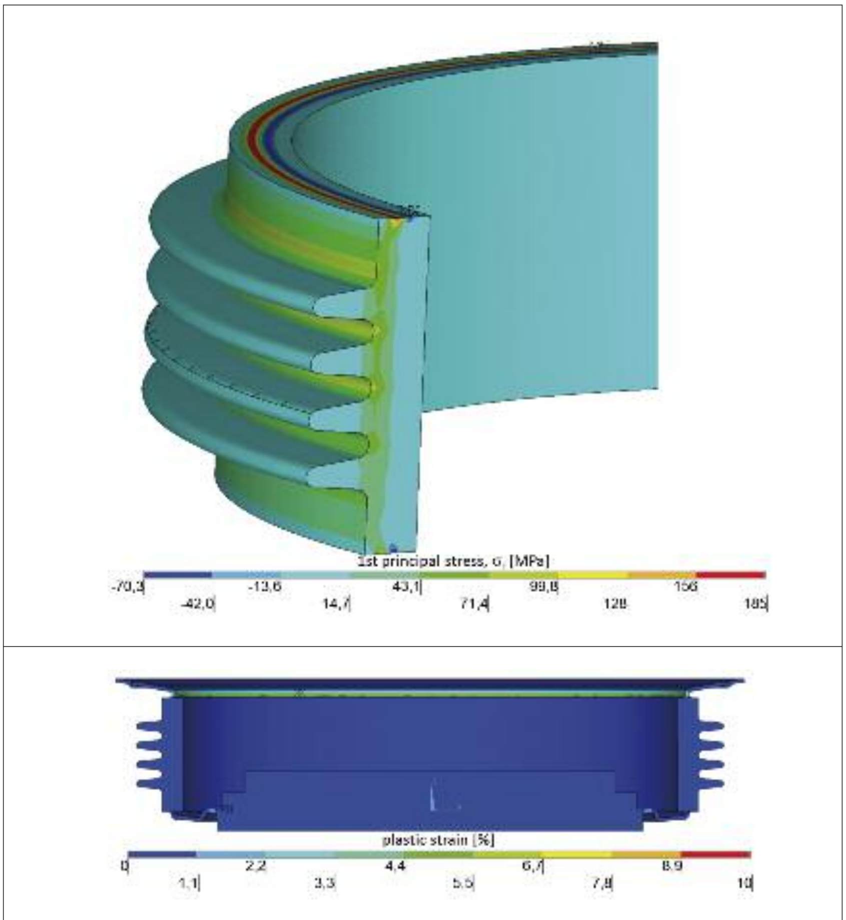

Fig. 4
Thyristor housing, contact piece ideal concentrically aligned, braze thickness 100 µm
upper: 1st principal stress in ceramic housing;
lower: plastic strain in copper parts and braze

Applied simplification for FEA

To reduce CPU-time for the FEA model some simplifications were made. The gate connector is located so that a mutual interference of the gate pin joint and the blade joint on the edge of the ceramic housing can be ruled out. Hence the gate pin joint can be simulated in an extra FEA. The resulting short-term fracture probability can be superimposed on the fracture probability of an insulator housing without gate hole.

For the assessment of the ceramic component the braze joint between membrane and contact piece as the cold welded joint between flange and membrane is not modeled, because these joints areas of influence do not affect the ceramic component. Thus membrane and contact piece as flange, membrane and contact piece are modeled as a homogenous material.

No material properties for the metallization layer and nickel plating were available. So these two layers were neglected in the model. In the FE model the braze is in direct contact with the ceramic. The semiconducting package was not modeled either. The influence of the package was modeled by an external displacement applied on the contact pieces interior surface.

Joining stresses

The calculation of the joining stresses is done by the following scheme:

- Uniform heating of the components up till brazing temperature (820 °C). Hereby each component is assumed free of residual- and joining stresses.
- Closing of the contact. With change of temperature joining stresses can be induced in the components.
- Uniform cooling from brazing down to room temperature. It is assumed that the cooling down will be a slow and controlled process that the component has a uniform temperature during the whole process.

After the cooling down to room temperature a multiaxial joining stress state has ensued. The assessment of the resulting joining stresses is dependent on the particular material. The short-term fracture probability is calculated for the ceramic component. For the metallic components the von-Mises stress and possible plastic strains are investigated. Hereby it is as-

sumed that the braze material can withstand large plastic strains without failure.
With these criteria different geometric variants of the thyristor can be compared in terms of their short-term fracture probability and the stress in the metallic parts. The results are listed in Tab. 2 and Fig. 4.
Aim of the investigation was the influence of the braze thickness and the positioning of the contact pieces to each other on the fracture probability of the ceramic housing. The insulator housing is maximal stressed on the outside of the housing-flange joint. This can be explained by the deformation of the flange during the brazing process. The flange curves upward due to the different coefficients of thermal expansion of copper and alumina. The deformation of the flange induces a bending moment in the braze joint. The lower braze joint is mostly exposed to shear stresses. The induced 1st principal stresses here are lower compared to the stresses induced in the upper joint. Additionally braze and copper flange in the area of influence of the joint are highly stressed. The plastic strain in the braze reaches values of 11 % locally. The values of the short-term fracture probability show a visible influence of the positioning, but the effect is negligible. Same can be seen for the influence of the braze thickness.

Loading stresses

After cooling down to room temperature the upward curved flange will be bent back into position and the semiconducting package will be placed between the upper and lower contact pieces. The loading stresses of the final assembly will be superimposed on the joining stresses calculated in the last step. Short-term fracture probability, equivalent stresses and plastic strain are set in relation to each other similarly to the procedure in the evaluation of the joining stresses.
By bending the flange back into position and the insertion of the semiconducting piece both contact pieces perform a forced movement. The upper contact piece moves up, the lower contact piece moves down. So flange and membrane are deformed and bending moments impact on both braze joints. The bending moment induced by the loading has the opposite direction compared to the bending moment induced by the joining process. Therefore

Tab. 3
Results of the FEA, combined loading and joining stresses

Load Case	**F_{ges} [%]**	**V_{eff} [mm³]**	**$\sigma_{I,max}$ [MPa]**	**$\sigma_{v.M,braze}$ [MPa]**	**$\varepsilon_{plast,braze}$ [%]**	**$\sigma_{vM,copper}$ [MPa]**
Contact piece ideal concentrically aligned, braze thickness 100 µm	$0,102 \cdot 10^{-5}$	20,07	92,7	263	10	240
Contact piece ideal concentrically aligned, braze thickness 80 µm	$0,847 \cdot 10^{-6}$	23,1	91,3	286	9,5	239
Contact piece ideal concentrically aligned, braze thickness 120 µm	$0,111 \cdot 10^{-5}$	21,7	93,2	294	10,8	239
Lower contact piece +0,5 mm and upper contact piece -0,5 mm shifted out of the center in x-direction, braze thickness 100 µm	$0,192 \cdot 10^{-5}$	7,81	102,9	271	10,1	244
Lower contact piece 0,5 mm shifted in y-direction, upper contact piece 0,5 mm shifted in x-direction, braze thickness 100 µm	$0,204 \cdot 10^{-5}$	7,62	103,4	273	10,1	243

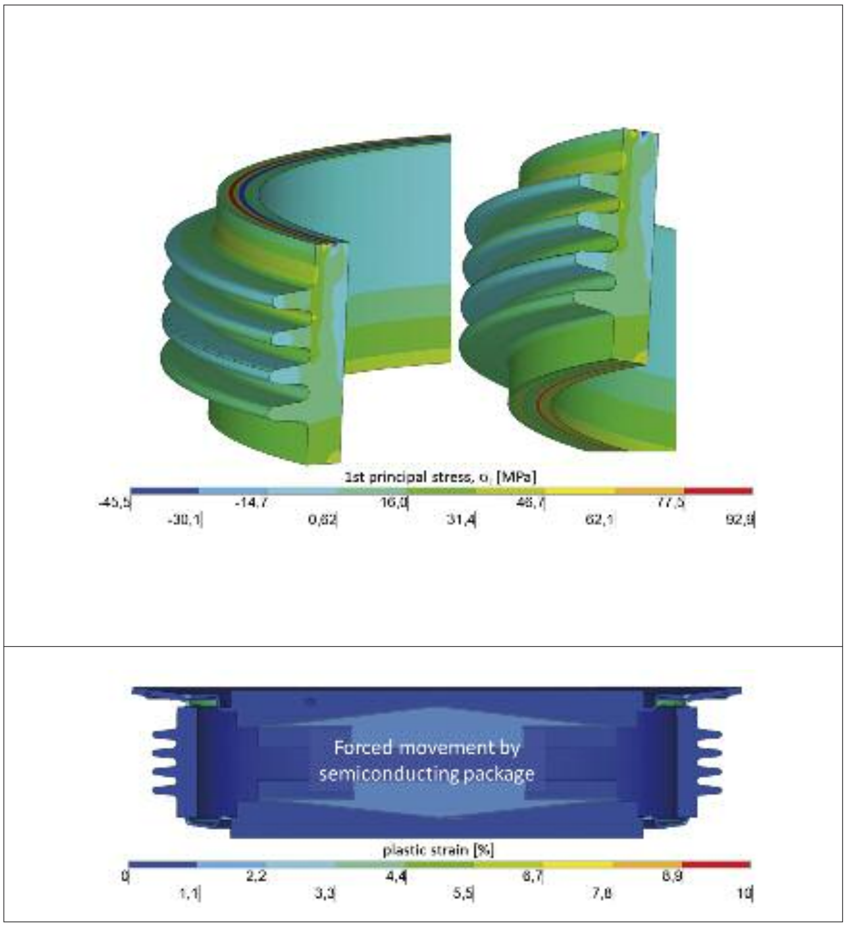

Fig. 5
Thyristor, contact piece ideal concentrically aligned, braze thickness 100 µm
upper: 1st principal stress in ceramic housing;
lower: plastic strain in copper parts and braze

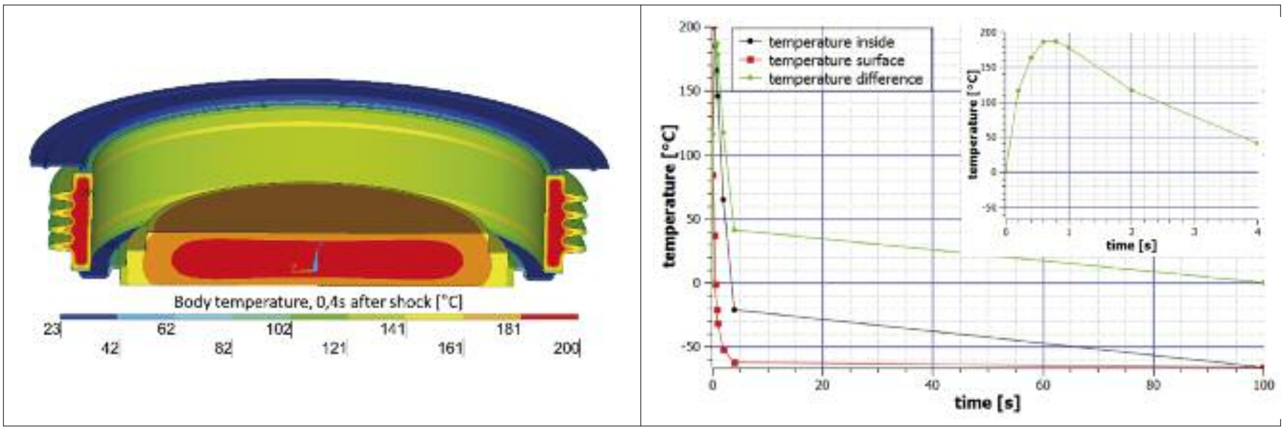

Fig. 6
Temperature field during thermal shock testing

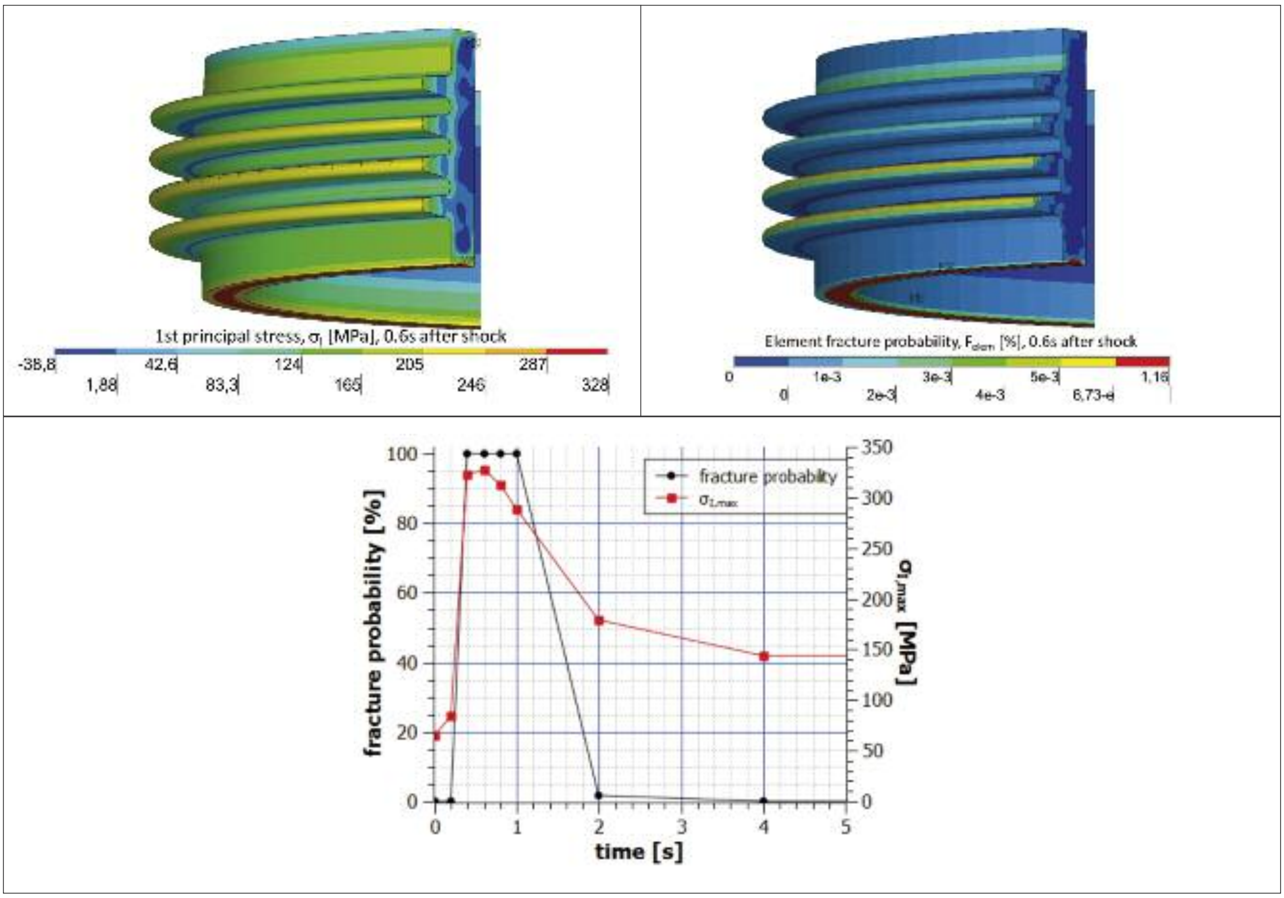

Fig. 7
Joining stresses superimposed with thermal induced stresses and resulting short-term fracture probability

the maximum principle stresses induced in both joints on the ceramic side are reduced. This results in the reduction of the short-term fracture probability. Here also effects of the positioning and the braze thickness can be seen, but the effect is negligible, too. Based on these results, further steps to increase efficiency measures can be discussed with a customer.

Prescribed test

Finally a prescribed test method for thyristor housings shall be investigated more deeply. In the test method a thermal shock test has to be passed through several times and the the housing has to be tested for vacuum tightness. For the thermal shock test the housing assembly will be heated up to 200 °C and the be shocked down to –65 °C in dry ice cooled methanol [3] after 5 min of natural cooling at room temperature. The result of this test shall help to evaluate the quality of the ceramic/metal assembly.

For the calculation of the temperature field a heat transfer coefficient α = 5000 W/m² · K was applied on the free surfaces of the components to simulate the thermal shock. Because of the vague description of the 5 min natural cooling at room temperature this step is not considered in the simulation. The thyristor housing is shocked from 200 °C directly to –65 °C. This means the induced stresses in the calculation will be higher than in the actual test. After 0,2 s a temperature field with very high gradients in the ceramic component develops (Fig. 6). This results in very high first principal stresses and short-term fracture probabilities (Fig. 7). The calculated first principle stresses in the ceramic reach values of up to 320 MPa after 0,4–1 s after the thermal shock in the area of the lower braze joint. The corresponding short-term fracture probability is 100 %. Such a probability of failure is not observed in carried out test. This is attributed to the harsher boundary conditions applied in the simulation. With the shown element short-term fracture probability (Fig. 7 right) critical regions in the ceramic body can be identified. It is visible that the lower braze joint is maximum stressed. But other parts of the ceramic body are also highly stressed (for example the rips), so it is not impossible that fracture can occur in these regions also. But it can be seen that the prescribed test method is applicable to test the braze joint. The flange-housing braze joint indeed is slightly stressed by this method so the test gives a very limited predication about the quality of this joint.

Influence of the Weibull-parameters

For the calculation of the short-term fracture probability the Weibull-parameters m and σ_{0V} are needed. They are usually measure in a 3- or 4-point-bending-test. At least 15–20 specimens should be tested in order that the underlying statistical analysis is as exact as possible. The determination of the Weibull-modulus is done using the maximum-likelihood-method (see eq. 6) [4]. The parameter σ_0 is calculated with eq. 7. The characteristic strength σ_{0V}, normed on an effective volume of 1 mm³, is calculated via the size-effect equation using the parameter σ_0 and the effective volume depending on the test that was carried out.

$$\frac{n}{m} + \left(\sum_{i=1}^{n} \ln(\sigma_i)\right) - n\frac{\sum_{i=1}^{n} \sigma_i^m \ln(\sigma_i)}{\sum_{i=1}^{n} \sigma_i^m} = 0 \quad (6)$$

$$\sigma_0^m = \frac{1}{n}\sum_{i=1}^{n} \sigma_i^m \quad (7)$$

But the measured fracture forces, which are used to calculate the Weibull-parameters, are error-prone. The influence of an error during the measurement of the fracture force during a 4-point-bending test shall be exemplified here. It is assumed that the measurement of the fracture force is exact but has an uncertainty of ±0,2 %. This results in an uncertainty of ±1 MPa when the fracture bending stress is calculated out of the force measurements. In an exemplary calculation the extreme values of the Weibull-modulus will be determined by the quantity of 18 specimens tested. It is assumed that either the calculated fracture stress for one specimen is right as measured or can deviate by ±1 MPa. This means that a total of 3^18 unique combinations are possible. The resulting Weibull-moduli are sorted in classes. The results are shown in Fig. 8. The evaluation of the

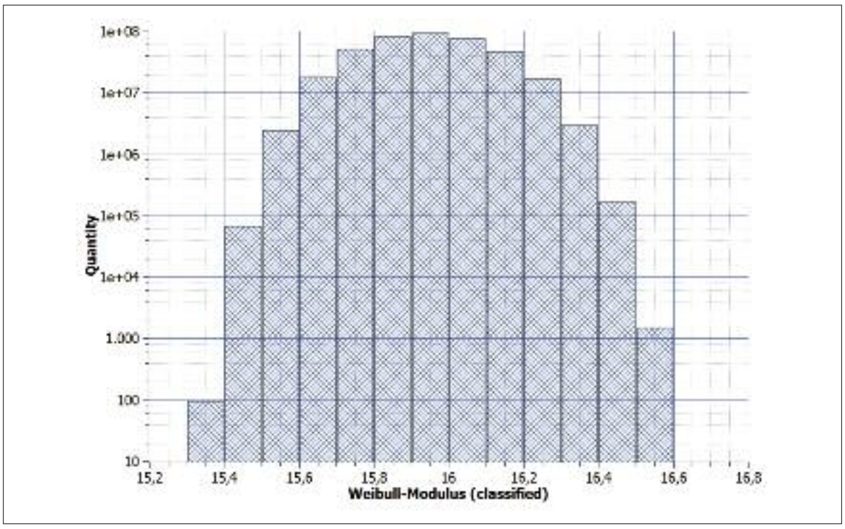

Fig. 8
Classification of the Weibull-parameter m

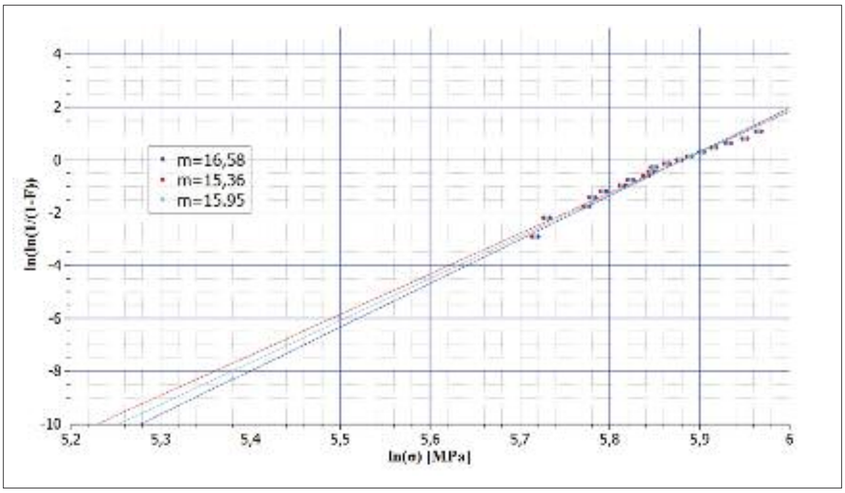

Fig. 9
Weibull-plot for: a) unchanged measurement data (m = 15,95),
b) measurement data variation with maximum Weibull-modulus (m = 16,58) and
c) measurement data variation with minimum Weibull-modulus (m = 15,36)

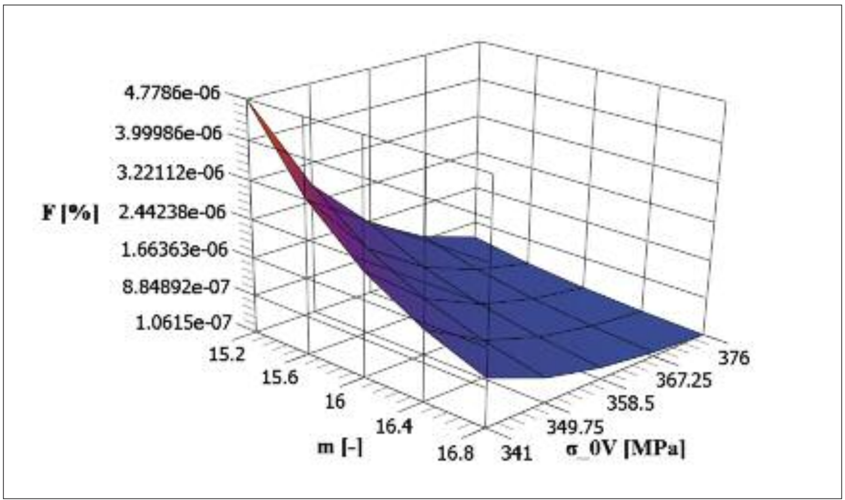

Fig. 10
Short-term fracture probability of a thyristor with superimposed joining and loading stresses depending on m and σ_{ov} with a variance with of 5 %

original measurement values gives the following Weibull-parameters: m = 15,95, σ_0 = 358,5 MPa. Most of the Weibull-parameters belong to the class of 15,9 < m < 16. The extremes are m_{min} = 15,36 and m_{max} = 16,58. The variation of the parameter σ_0 is very small: 357,7 MPa < σ_0 < 359,7 MPa. The Weibull-plot for the extremes and the original measurement data is given in Fig. 9.

The effects of the uncertainties regarding the Weibull-parameters m and σ_{0V} on the short-term fracture probability are shown by the example of a thyristor with superimposed joining and loading stresses (Fig. 10). For both parameters an interval of uncertainty of 5 % was assumed. The extreme values for the short-term fracture probability are

F_{max} (σ_{0V} = 341 MPa, m = 15,2) =
47,8 · 10^{-7} % and F_{min}(σ_{0V} = 376 MPa,
m = 16,8) = 1,06 · 10^{-7} %.

Conclusion

With the FEA as a part of the integrative design process it is possible to precisely calculate the stresses, which are induced in ceramic components during the assembly or operation. By using postprocessors short-term and also long-term fracture probabilities can be calculated. The precision of the results depends highly on the used input data and the introduced model simplifications. The Weibull-parameters are calculated from measurement data. It was shown that even small measurement errors can affect the Weibull-parameters that the resulting short-term fracture probability can differ by a factor >> 10. Therefor an alignment of calculated and observed fracture probability is hardly achievable.

Nevertheless FEA is a powerful tool for the numerical component designing of ceramic/metal assemblies. It is possible to compare different component designs in a short time. So when using FEA from the scratch the prototype phase can start with an optimized design. This means saving of time and cost by the reduction of non-optimized prototypes. The delivery time for prototypes often ranges between 8 and 12 weeks. So it's possible to save about 20–30 weeks by the use of optimized designs. In contrary to that 1–4 weeks of simulation time have to be accounted for common components. *LAPP Insulators Alumina* develops ceramic/metal assemblies with the customer up to production stage. Cost of carried out FEA is partly credited on serial components order. Also commissioned works are available for customers. Cost of the FEA often ranges beneath the tooling-cost of initial samples.

The application of FEA will not completely be the end "trial and error", but this method will help to reduce the number of "trial and error" cycles for finding the final and functioning component.

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