FEA – a Key Technology for Integrative Design of Ceramic-metal-assemblies

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 material laws than for example steel, this method is not wide spread yet.

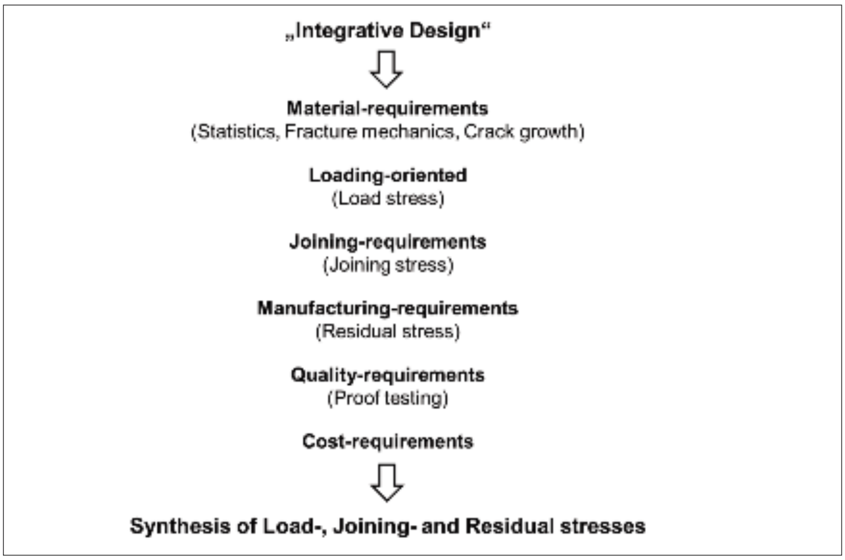


Fig. 1
Integrative design with ceramics (translated from [1])

Introduction
To determine the reliability of highly stressed components that 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 made by means of observations 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]. This process can be either applied to the new construction or the reevaluation of existing designs and processes to assess necessary rationalization measures to increase efficiency.

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

Fig. 1 shows the approaches of the integrative design with ceramics to achieve the synthesis of joining-, loading- and residual stresses. In this article the focus lies on the joining oriented design of a ceramic-metal braze joint.
Using the example of a vacuum feedthrough (Fig. 2), manufactured by *LAPP Insulators Alumina GmbH,* the possibilities which arise from the use of FEA shall be pointed out. For this purpose a re-

Fig. 2
Vacuum thermocouple feedthrough

Dr Kai Sauerzapfe,
Dr Holger Wampers
LAPP Insulators Alumina GmbH
96257 Redwitz
Germany

www.lappinsulators.com/alumina
ksauerzapfe@lappinsulators.com

design of a vacuum feedthrough is discussed in the following.

The feedthrough is a running article and the customer wants to have a stiffer metal component at the tip of the feedthrough. In the current design this was made by NiFe42 what fits well to the alumina ceramic body with its controlled CTE between 4,5–12,5 10^{-6}/K (Fig. 3). The change of the material with higher stiffness will lead to a complete other stress distribution in the joint area. This will probably cause a higher risk of rupture of the component. To evaluate this prior to a trial and error process it was decided to build up four models and calculate the joint before making trials what would be cost and time consuming with an unsure end result.

It was decided to use pure nickel as a replacement material. The course of the coefficients of thermal expansion for the materials used is given in Fig. 3. To show the relevant differences in thermal expansion in this figure the reference temperature was set to 780 °C – the liquidus temperature of the braze – and recalculated. So at a temperature of 20 °C the differences in the coefficient of thermal expansion can be seen that will induce the joining stresses in the components. It is apparent that the CTE of NiFe42 is better matched with the CTE of alumina than pure nickel is. So the resulting joining stresses will rise when

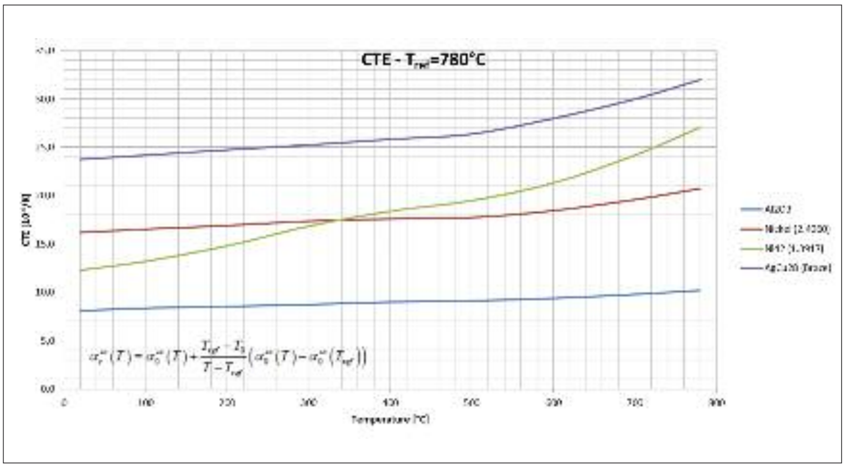
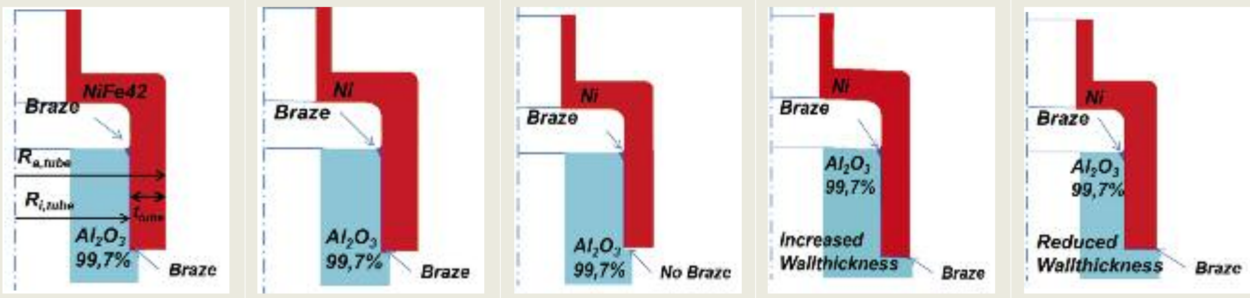


Fig. 3
Coefficients of thermal expansion for selected materials, reference temperature T_{ref} = 780 °C

Tab. 1
Material properties

Material	$E_{20\,°C}$ [GPa]	$\nu_{20°C}$ [–]	$\alpha_{20\,°C \rightarrow 780\,°C}$ [10^{-6}/K]	$R_{p0,2}$ [MPa]	
Ni	205	0,29	16,2	142	
NiFe42	142	0,30	12,3	270	
AgCu780	98	0,34	19,8	112	
	$E_{20°C}$ [GPa]	$\nu_{20°C}$ [–]	$\alpha_{20 \rightarrow 780}$ [10^{-6}/K]	$\sigma_{0V,\,20\,°C}$ [MPa]	$m_{20\,°C}$ [–]
Al_2O_3 (99,7)	380	0,22	8,1	422	11



NiFe42-Tube	Ni-Tube-X	Case 2	Case 3	Case 4
t_{tube} = 0,6 mm	0,5 ≤ t_{tube} ≤ 1,2 mm	t_{tube} = 1 mm	t_{tube} = 1 mm	t_{tube} = 1 mm
R_{a,Al_2O_3} = 4,2/4,5 mm	R_{a,Al_2O_3} = 4,2/4,5 mm	R_{a,Al_2O_3} = 4,2/4,5 mm	R_{a,Al_2O_3} = 4,2/5,4 mm	R_{a,Al_2O_3} = 3,5/4,5 mm
horizontal and vertical brazing	horizontal and vertical brazing	vertical brazing	horizontal and vertical brazing	horizontal and vertical brazing

Fig. 4
Load case description

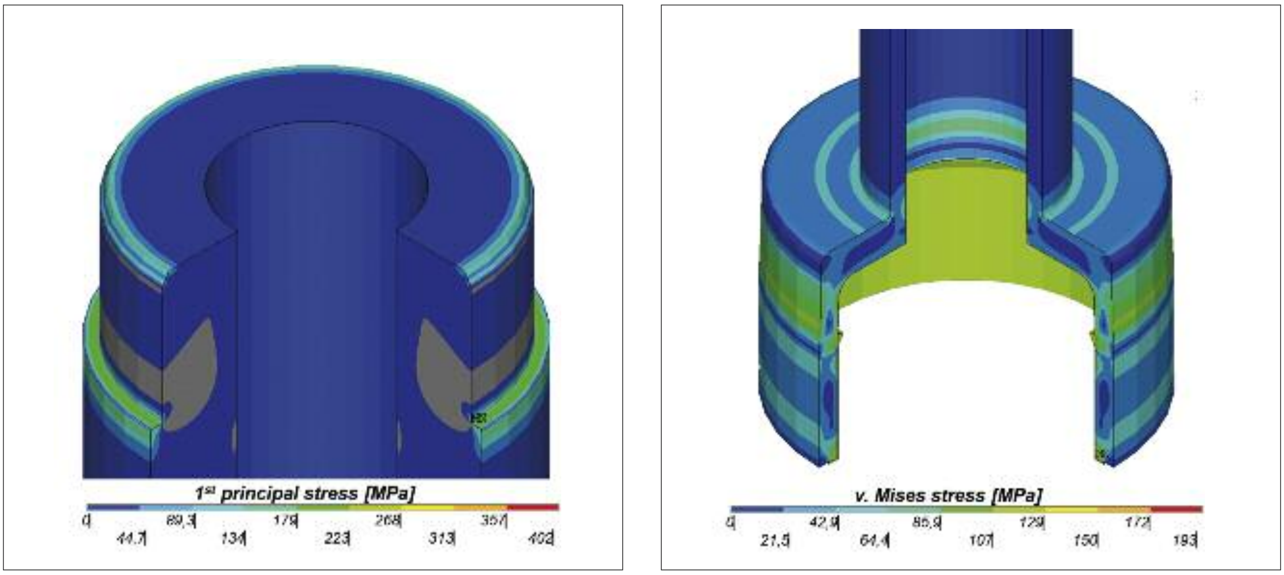


Fig. 5
Joining stresses for NiFe42-Tube, 1st principal stresses in the ceramic (left) and v. Mises stresses in NiFe42 tube and braze (right)

the material is changed from NiFe42 to nickel on a 1:1 basis.
Due to the running production for this article, tools for the ceramic body and metal parts are existent.

Material properties

The material properties used for the FEA are listed in Tab. 1. Material properties for NiFe42 are taken from data provided by *Deutsche Nickel GmbH* [2]. The material properties form the data provided by *Special Metals Corporation* [3]. For the calculation temperature dependent values were used.

Load cases

Fig. 4 shows the load cases that were investigated by FEA. The first case was the original design using NiFe42 as tube material. The tube has a wall thickness of 0,6 mm and is brazed horizontally (circumference joint on the shoulder surface) and vertically (circumference joint on the mantle surface) to the alumina. 99,7 % Alumina is used as a ceramic body. The borehole diameter in the ceramic is 4 mm and held constant for all simulations. The outer diameters of the ceramics are 8,4 mm and 9 mm. In the second model NiFe42 was replaced with nickel as tube material. The dimensions of the ceramic part were held constant, the wall thickness

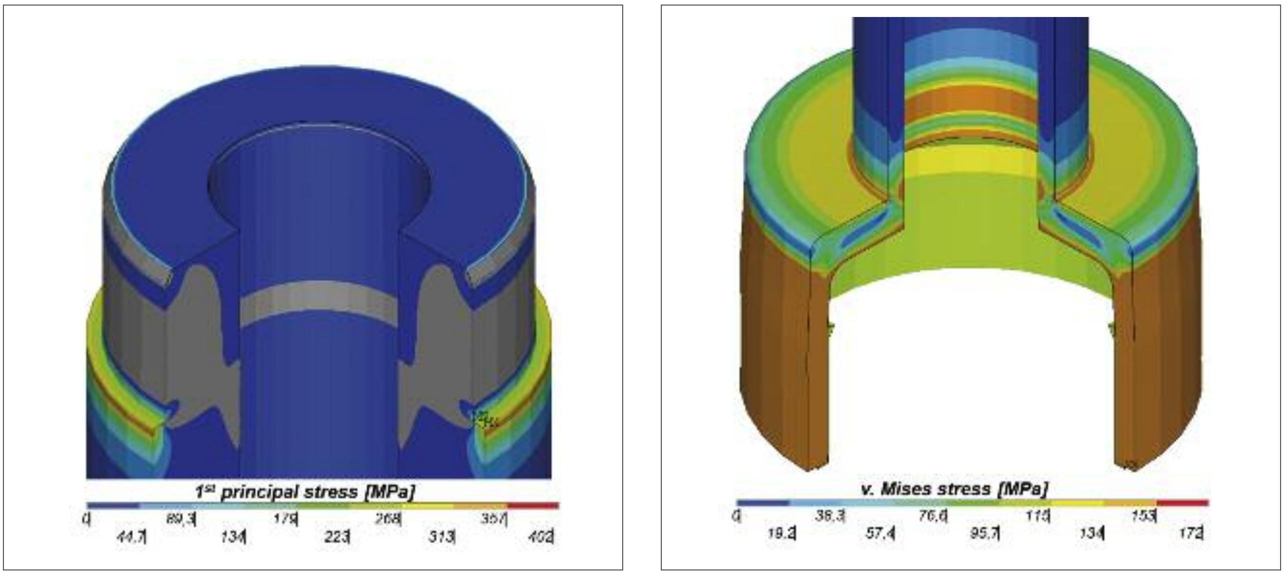


Fig. 6
Joining stresses for Ni-Tube-2, 1st principal stresses in the ceramic (left) and v. Mises stresses in Ni tube and braze (right)

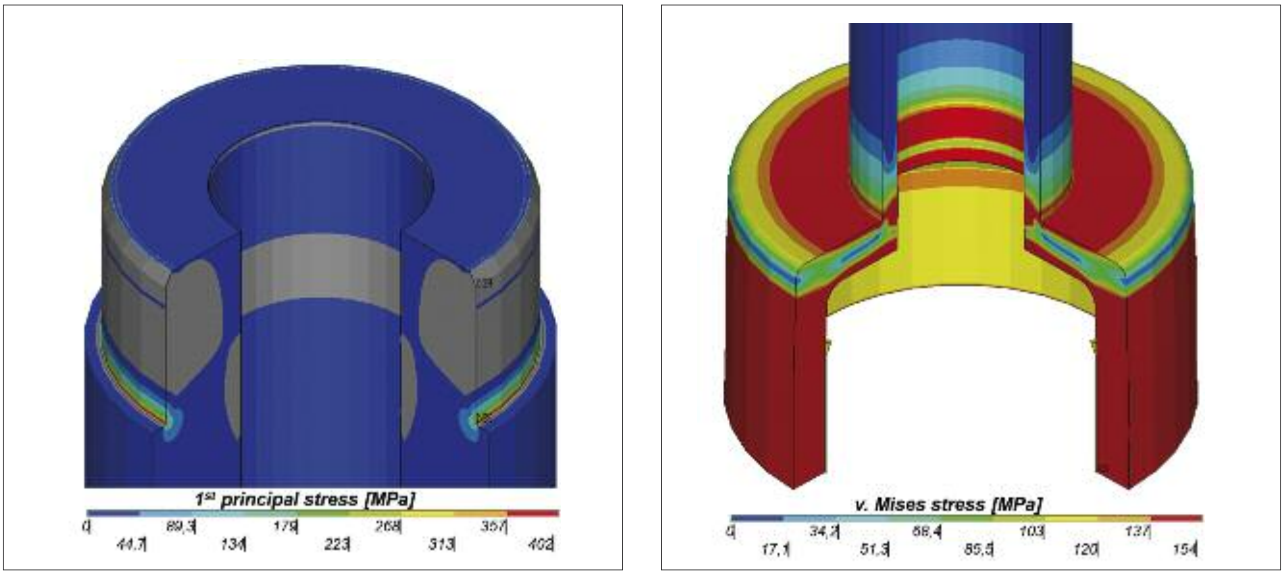


Fig. 7
Joining stresses for case 2, 1st principal stresses in the ceramic (left) and v. Mises stresses in Ni tube and braze (right)

of the nickel tube was varied between 0,5 mm and 1,2 mm. The tube was brazed horizontally and vertically to the ceramic. In case 2 a nickel tube with a wall thickness of 1 mm was vertically brazed to the ceramic. The horizontal brazing was left off. In case 3 the outer diameters of the ceramic were changed to 8,4 mm and 10,8 mm. So the wall thickness of the ceramic was increased. The nickel tube with 1 mm wall thickness was brazed horizontally and vertically. In the last case the wall thickness of the ceramic was reduced. The outer diameters were changed to 3,5 mm and 4,5 mm, so the overall outer dimensions are the same as the original component. This has the advantage that a possible new design can replace the old one in a 1:1 basis and the surroundings don't have to be changed. The 1 mm nickel tube is brazed horizontally and vertically.

In the following figures (Fig. 5–9) the results of the FEA are shown. The color scaling for the ceramic parts are held constant for each load case so the colors can be compared directly. For the ceramic part only tensile stresses are shown. Regions where compression stresses are induced are shown as gray color since compression stresses don't contribute to the component fracture probability *F* calculated by the following equation [4]:

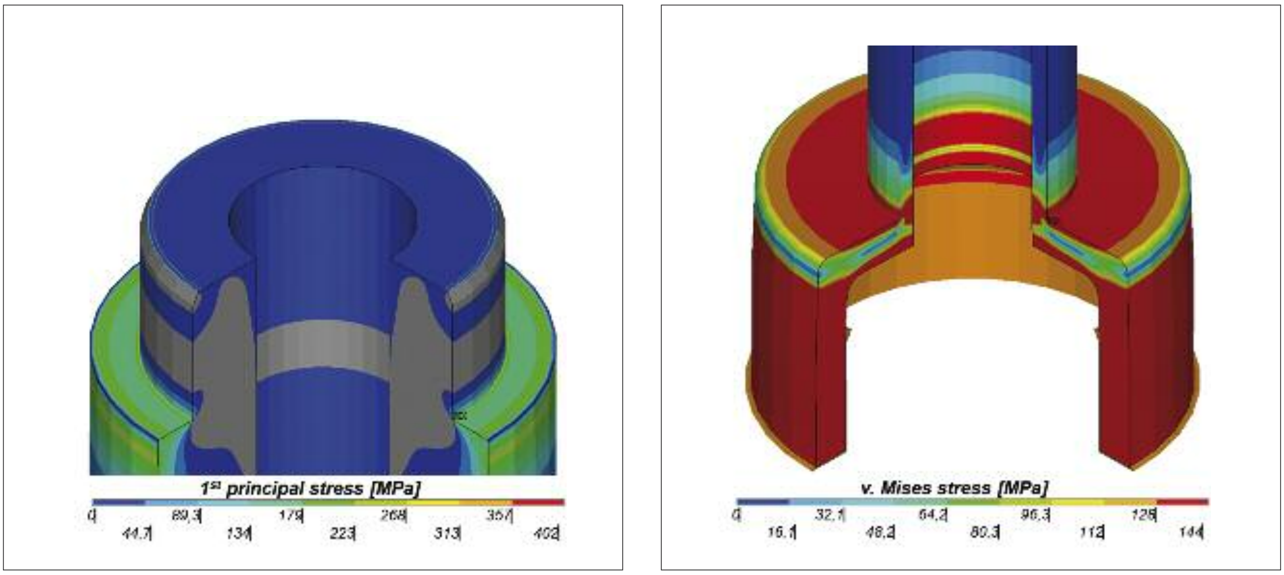


Fig. 8
Joining stresses for case 3, 1st principal stresses in the ceramic (left) and v. Mises stresses in Ni tube and braze (right)

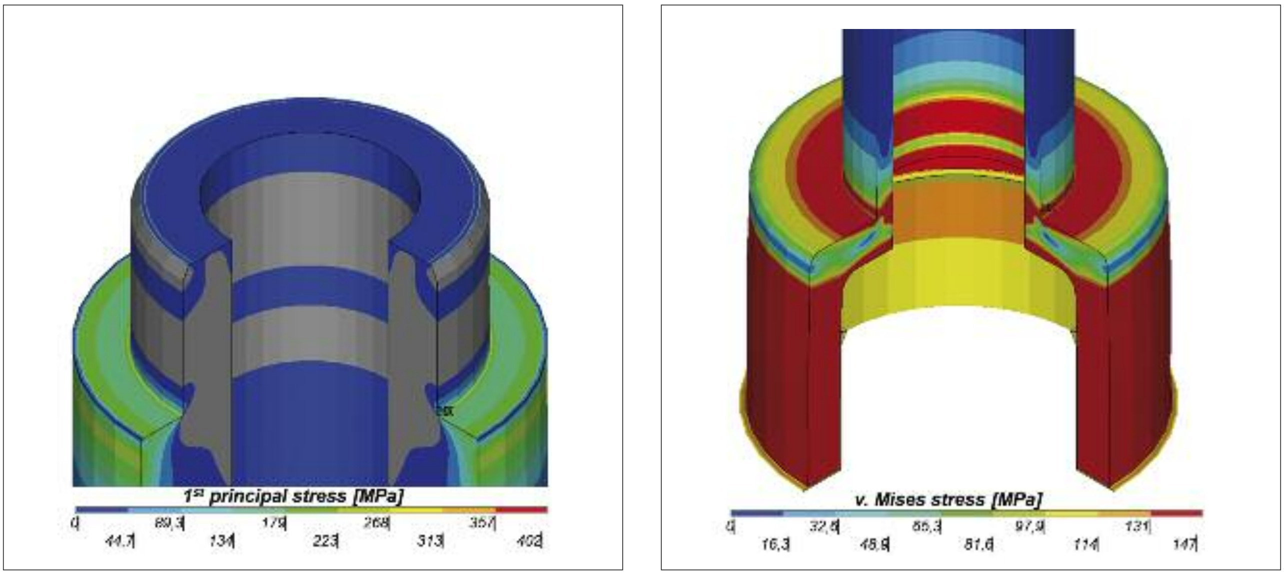


Fig. 9
Joining stresses for case 4, 1st principal stresses in the ceramic (left) and v. Mises stresses in Ni tube and braze (right)

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

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

The term σ *(x, y, z)* is evaluated only for tensile stresses.

Tab. 2
Load cases and results

Modell	$\sigma_{1max,ceramic}$ [MPa]	$F_{Ceramic}$ [%]	$\varepsilon_{plast,tube}$ [%]	t_{tube} [mm]	$R_{a,tube}$ [mm]	$R_{i,tube}$ [mm]
NiFe42-Tube	224,8	0,0017	2,20	0,6	4,8	4,2
Ni-Tube-1	352,2	0,6737	2,53	0,5	4,7	4,2
Ni-Tube-2	359,0	1,1114	2,80	0,6	4,8	4,2
Ni-Tube-3	361,0	1,5363	2,94	0,7	4,9	4,2
Ni-Tube-4	361,8	1,9030	2,98	0,8	5	4,2
Ni-Tube-5	362,2	2,1779	3,01	0,9	5,1	4,2
Ni-Tube-6	362,3	2,3519	3,06	1,0	5,2	4,2
Ni-Tube-7	362,2	2,4533	3,13	1,1	5,3	4,2
Ni-Tube-8	362,1	2,5239	3,21	1,2	5,4	4,2
Case 2	401,0	0,1849	1,52	1,0	5,2	4,2
Case 3	288,9	0,1519	2,16	1,0	5,2	4,2
Case 4	298,4	0,1449	2,28	1,0	4,5	3,5

Results

The results are also summarized in Tab. 2 and Fig. 10. The fracture probability in Tab. 2 is listed with 4 digits just for reasons of distinguishability. The achievable accuracy will rather lie in the region of the first digit. In the original design the maximum 1st principal stresses induced into the ceramic part reach 224,8 MPa. This results in a fracture probability of 0,0017 %. If the NiFe42 tube is replaced with a nickel tube and the other parameters are held constant, the maximum 1st principal stress rises to 359 MPa and the fracture probability to 1,1 %. So the fracture probability is increased by a factor of 640. In both cases the maximum stresses are induced at the shoulders edge. Since the CTE of nickel is higher than the CTE of NiFe42 the shrinkage of the tube induces more compression stresses in the ceramic in the second case. This also explains the higher tensile stresses in the edge region of the shoulder.

If the tube is brazed vertically only then the value of the maximum principal stress rises compared to the original design. The fracture probability decreases though compared to case Ni-Tube-6 (Tab. 2). For these two cases the wall thickness of the nickel tube is the same so these are directly comparable. The reduction of the fracture probability can be explained by the smaller effective volume compared to Ni-Tube-6. As a result of the smaller volume in which the tensile stress is induced the chance of a fracture triggering fault is reduced. This comparison shows the necessity of ceramic specific postprocessors. If just the height of the maximum induced stresses are used for the design of ceramics wrong conclusions are drawn.

In case 3 the joining stresses could be reduced compared to case 2 by a factor of 1,4. The fracture probability is reduced only by a factor of 1,2. This represents the influence of the effective volume. The effective volume for case 2 is $V_{eff,case2}$ = 0,0033 mm³ for case 3 it is $V_{eff,case3}$ = 0,0981 mm³.

In case 4 the dimensions of the ceramic were reduced. For this case higher stresses and higher fracture probabilities were expected. But the increase of the maximum induced principal stress is very small and the fracture probability could still be reduced compared to case 3. This is mainly because the region in the ceramic with the reduced wall thickness is mainly loaded with compression stresses. Compared to the case Ni-Tube-6 the fracture probability could be reduced by a factor of 16,2. Compared to the original design the fracture probability is increased only by a factor of 85 and not 640 if the original design with a 1 mm Ni tube is used.

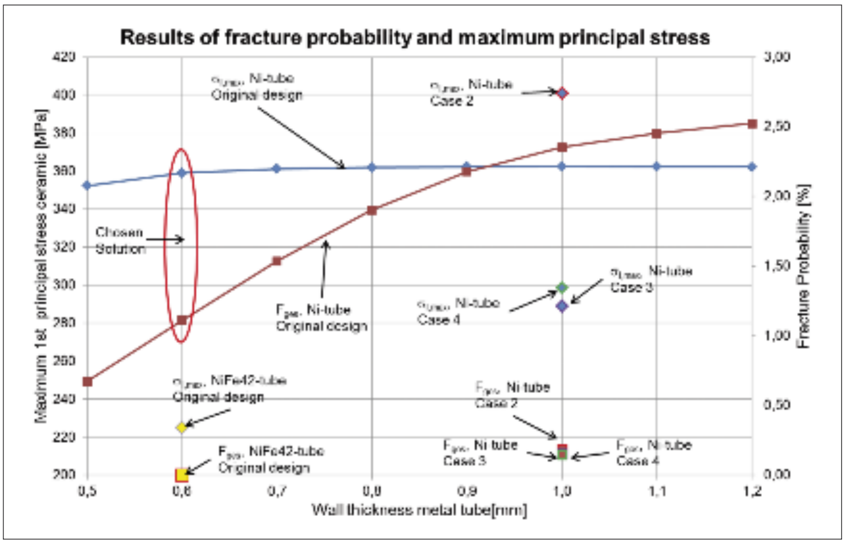


Fig. 10
FEA results

Conclusion

It has been shown that the FEA as a tool for the integrative design with ceramics could be used for the redesign of ceramic-metal-assemblies. Different solutions were presented and evaluated regarding induced stresses and fracture probabilities of the ceramic body (Fig. 10). It was shown that it is possible to substitute the original NiFe42 with a stiffer nickel tube and keep the increase of the fracture probability low. The results were discussed with the customer and in the end the design Ni-Tube-2 was chosen for production since for every other case new cold drawing tools for the metal tube would have to be procured. During the production of the new part no failures were observed till now. In this particular case the redesign on a 1:1 basis was possible even if the fracture probability is increased by the change of the material. In other cases a pure material substitution can result in severe problems which result in a time consuming process of trial and error.

LAPP Insulators Alumina develops ceramic/metal assemblies with the customer up to production stage. Cost of the FEA often ranges beneath the tooling-cost of initial samples and the time to market can be reduced drastically.

References

[1] Maier, H.R.: Integratives Konstruieren mit Keramik. Proc. Abschluss-Symposium des BMBF-Verbundprojekts Keramische Komponenten für das Spritzgießen und Extrudieren. Ed. G. Wötting (2005) 24–47

[2] Deutsche Nickel GmbH, http://www.deutsche-nickel.de/produkte/pdf/dilatone_deutsch.pdf (in German)

[3] Special Metals Corporation, http://www.specialmetals.com/documents/Nickel%20200%20&%20201.pdf

[4] Munz, T.; Fett, D.: Ceramics, mechanical properties, failure behaviour, materials selection. Berlin, Heidelberg 1999