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Design of Thermally High-Loaded Ceramic Components for Gas Turbines

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Abstract

The excellent high-temperature properties of ceramics offer great potential for their application in gas turbines. However, ceramics lack the ability to reduce local stress concentrations by plastic deformation. As a result, stresses that are caused by different local thermal expansions can reach critical values, especially in the hot-section components. To improve the reliability of ceramic components, the temperature differences have to be reduced. At the Institut für Thermische Strömungsmaschinen (ITS) a systematic methodology for designing thermally high-loaded components has been developed. The principles of the design procedure include a segmentation of the parts according to the load and a three-layered construction of the component's wall. The inner hot-gas ducting layer consists of a high-temperature resistant ceramic material which is embedded into a metal containment by a flexible ceramic fibre insulation. By adjusting the individual thicknesses of the ceramic and the insulation layers according to the local boundary conditions on the hot-gas side, the local temperature differences in the ceramic can be considerably reduced. Finite element analyses of the temperature and stress distribution for first stage nozzle guide vanes and the vaneless scroll of a radial gas turbine are shown. Compared with conventional designs, the calculations clearly demonstrate that the hybrid wall construction and an ingenious segmentation of the components lead to a significant reduction in the stress level. The reliability improvement is documented by failure probability calculations performed using the ITS fracture statistics code CERITS. © 1997 Elsevier Science Limited.

Nomenclature

a	thermal diffusivity (m^2/s)
d	wall thickness (mm)
h	heat transfer coefficient (W/m^2K)
m	Weibull modulus
n	crack growth parameter
t	time (s)
x	distance normal to surface (mm)
B	crack growth parameter
K	stress intensity factor (MPa $m^{1/2}$)
R	radius of curvature (mm)
T	temperature (K)
V	volume (mm^3)
α_1	parameter used in Richard criterion $\alpha_1 = K_{Icrit}/K_{IIcrit}$
λ	conductivity (W/mK)
ν	Poisson's ratio
σ	stress (MPa)
τ	shear stress (MPa)
θ, ϕ	angle (degrees)

Subscripts:

0	unit
I	mode I
II	mode II
cool	cooling air
corr	corrected
crit	critical
eq	equivalent
hot	hot-gas
max	maximum
min	minimum
n	normal
C	ceramic
I	insulation
M	metal

1 Introduction

The application of ceramics to the hot-gas path of turbomachines requires new design methodologies. Due to their brittle behaviour, these materials are not able to reduce local stress concentrations by plastic deformation. Hence, the designer must provide a compliant support for the components.[1] In addition to this, the parts are thermally high loaded and as a consequence temperature gradients are induced in the components. Therefore, the stresses caused by different local thermal expansions can attain values that cause immediate failure of the components. This fact was not considered adequately by former designs, thus leading to insufficient reliability of ceramic gas turbine components.[2,3]

At the Institut für Thermische Strömungsmaschinen experimental and theoretical work aimed at the reliable design of ceramic gas turbine components has been carried out for several years. This paper presents a new systematic methodology for the design of thermally high-loaded ceramic components. It is based on the well-known design criteria such as avoiding point forces and stress concentrators (sharp corners, rapid changes in section size, undercuts, holes etc.), symmetrical design, preference for small components, etc., accompanied by an adjustment to the thermal load and ingenious segmentation.

Figure 1 gives a survey on the dominating parameters of the design process of ceramic components. To a certain extent these are the same as for the design of metallic parts; however, due to the inherent brittleness of ceramics, the local stress distribution plays an important role. Structural defects in ceramic components entail stress concentrations under load. Fracture mostly originates from these flaws. The flaw distribution in size and orientation, and hence, the mechanical properties, show large variations, which have to be described with statistical tools.

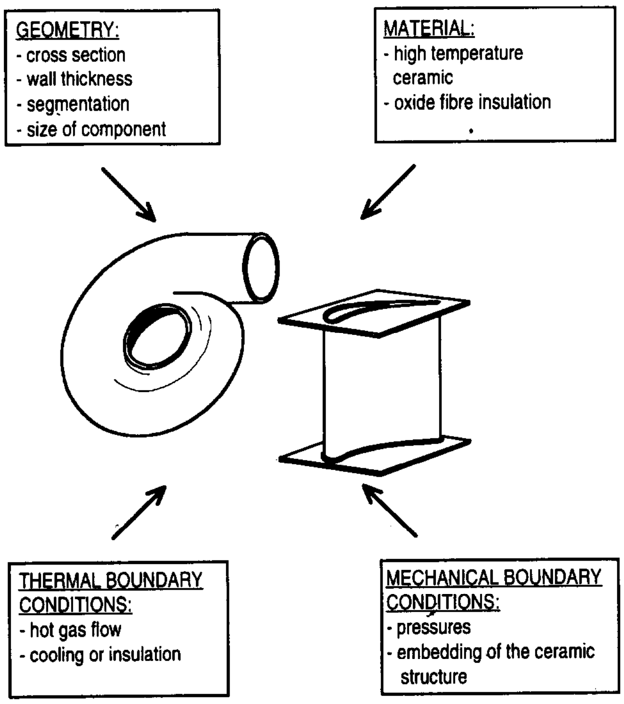

Fig. 1. Influences on ceramic component design.

2 Fracture statistics

Because of the scatter in strength inherent to brittle materials, statistical methods are employed for the reliability analyses of ceramic components. They can predict the failure behaviour of brittle materials subjected to arbitrary stress states. The fracture statistics computer code CERITS developed at the Institut für Thermische Strömungsmaschinen uses an extension of Batdorf's theory for polyaxial stress states.[4] It is assumed that the failures are solely caused by volume flaws.

The failure probability derived from Batdorf's model, which gives a better description of the physics of fracture than the pure extreme value statistics of Weibull, can be written as follows:

$$P_f = 1 - \exp\left[-\frac{1}{4\pi}\cdot\frac{1}{V_0}\int_V\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi}\left(\frac{\sigma_{\mathrm{Ieq}}}{\sigma_{\mathrm{I0}}}\right)^m \sin\theta\cdot d\theta\cdot d\phi\cdot dV\right] \quad (1)$$

In this equation σ_{Ieq} represents the equivalent stress and σ_{I0} and m are the material constants: the Weibull scale parameter and the Weibull modulus. The equivalent stress can be obtained from different fracture criteria in combination with two crack types (see Table 1).

Gas turbines must operate reliably for several thousand of hours. Therefore, lifetime prediction plays an important role in the assessment of the component's reliability. The fracture statistic program CERITS calculates the time dependent failure probability on the basis of subcriticial crack growth. Stürmer *et al.*[6] assume that the Batdorf model for a multiaxial stress state is valid not only for fast fracture but also for subcritical crack growth under a mixed mode load. Assuming a constant stress state, calculation of the time dependent failure probability is possible:

$$P_f(t) = 1 - \exp\left[-\frac{1}{4\pi}\cdot\frac{1}{V_0}\int_V\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi}\left(\frac{\left(\frac{t}{B}\sigma_{\mathrm{Ieq}}^n + \sigma_{\mathrm{Ieq}}^{n-2}\right)^{\frac{1}{n-2}}}{\sigma_{\mathrm{I0}}}\right)^m \sin\theta\cdot d\theta\cdot d\phi\cdot dV\right] \quad (2)$$

In this equation subcritical crack growth is described by the parameters B and n. A more detailed description of eqns (1) and (2) is given in Stürmer *et al.*[4,6] The calculations presented are

Table 1. Equivalent stress for different fracture criteria and crack types implemented in CERITS

Fracture criterion	*Crack type*	*Equivalent stress*
Normal stress	Sphere	σ_n
Strain energy release rate	Griffith crack	$\sqrt{\sigma_n^2 + \tau^2}$
Strain energy release rate	Penny shaped crack	$\sqrt{\sigma_n^2 + \frac{\tau^2}{(1 - 0{\cdot}5\nu)^2}}$
Richard[5]	Penny shaped crack	$\frac{1}{2}\left[\sigma_n + \sqrt{\sigma_n^2 + \frac{4\alpha_1^2\tau^2}{(1 - 0{\cdot}5\nu)^2}}\right]$

performed with the assumptions of the strain energy release rate criterion and penny shaped cracks, since these revealed the best agreement with experimental data.[7]

Ceramic materials have undergone a rapid development during the last years. The Weibull moduli representing the scatter of the material's strength have reached higher values and the high-temperature properties have been further improved. Also, the manufacture processes have become more reliable and are more advanced. Today it is possible to produce quite complex shapes out of ceramic materials with predictable properties. However, ceramics still cannot substitute their metallic counterparts in many applications. One reason is that ceramics require a different design procedure, especially if thermally induced stresses reach values that are not acceptable for reliable operation. Therefore, a structural adjustment of hot-section components to the thermal boundary conditions is imperative.

3 Thermal adjustment

Gas turbine components in the hot-gas section are exposed to high thermal loads. The load is not uniform since it depends on the local flow situation. In addition to this, the components are operated not only under stationary working conditions but also under transient conditions which are even more critical because of the rapidly changing gas temperatures.

The goal of the thermal adjustment proposed first by Gutmann[8] is a homogeneous temperature in all areas of the ceramic structure. The temperature differences across the wall thickness do not lead to high stress states since the occurring Biot-numbers are small. Hence, it is sufficient to demand a constant integrated mean wall temperature for all regions in the component;

$$\overline{T} = \frac{1}{d_C} \int_{x=0}^{d_C} T(x)\mathrm{d}x \qquad (3)$$

From Fig. 1 it can be seen that the adjustable parameters of a component design are the ceramic wall thickness and the thermal boundary conditions on the cool-gas side. The other influences shown are more or less fixed by the choice of the material and the thermodynamic layout. By introducing adjustable ceramic wall thicknesses, the component can be optimised for the transient working conditions. Under stationary conditions a hybrid wall construction consisting of a hot-gas resistant ceramic layer, which is embedded into a metal construction by a compliant insulation, helps to make the temperature distribution in the ceramic wall more uniform. This construction permits regulation of the local heat flux through the three-layered wall and therefore approaches a homogeneous mean wall temperature in the ceramic structure. For reasons of simplicity the analytical derivation of the optimisation criteria defining the required thicknesses of the ceramic and insulation layers was performed for plane walls and a constant hot-gas temperature. For the thermal optimisation the metal layer is of minor importance, but it has to support the hybrid construction and facilitates the integration of the part into the metal construction. A schematic of the three-layered wall is shown in Fig. 2.

In the first step the value of the local ceramic wall thickness has to be determined. This can be done by considering transient working conditions,

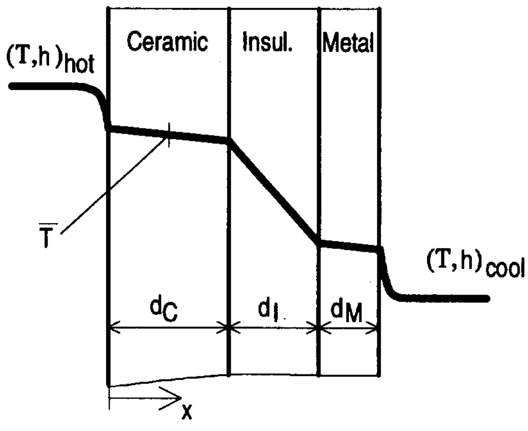

Fig. 2. Three-layered wall.

which are simulated by a rapid change in the hot-gas temperature. With a quasi-stationary approximation

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} = \text{const.} \tag{4}$$

and assuming an adiabatic back side of the ceramic wall, which is only correct for the first instant after the temperature jump, the following relation for the ceramic wall thickness can be derived:

$$\frac{d_C}{h_{hot}} + \frac{d_C^2}{3\lambda_C} = \text{const.} \tag{5}$$

This relationship means that the rate of heating of a solid body depends on its heat conductivity and mass in combination with the heat transfer to the boundaries. In the case of the plane wall the local mass is represented by the wall thickness. Since the heat conductivity has a given value, the ceramic wall has to be thick in areas with high heat transfer on the hot-gas side and thin in areas with low heat transfer.

As indicated earlier, the heat flux through the three-layered wall under steady state conditions has to be adjusted to the hot-gas boundary conditions. Therefore the local insulation thickness must be variable. In regions with high heat transfer coefficients the heat resistance has to be kept low by a thin insulation layer. In areas with low heat transfer, on the other hand, the thickness of the insulation should be higher to increase the local mean wall temperature. This principle can be described as follows:

$$\frac{\dfrac{d_C}{2\lambda_C} + \dfrac{d_I}{1\lambda_I} + \dfrac{d_M}{1\lambda_M} + \dfrac{1}{h_{cool}}}{\dfrac{1}{h_{hot}} + \dfrac{d_C}{2\lambda_C}} = \text{const.} \tag{6}$$

Equation (6) is derived from a stationary heat-flux calculation for a plane three-layered wall with constant local mean ceramic wall temperature.

Taking the curvature of the ceramic components into account, the changing heat transfer area has to be considered as in the case of heated or cooled pipes, for example. Thus cases have to be distinguished between where the heat transfer area on the hot-gas side is smaller or larger than the one on the cooling-gas side. With eqns (7) and (8) the corrected layer thicknesses can be calculated. They deliver an approximation of the results which can be obtained by an iterative heat transfer calculation for a three-layered cylinder performed under the same assumptions as for the three-layered flat wall. For the case of a smaller hot-gas side heat transfer area corresponding to an externally cooled pipe, the upper algebraic signs are valid. If the hot-gas side heat transfer area is larger than the one on the cool-gas side (externally heated pipe) the lower signs have to be employed.

$$d_{C,corr} = \pm R\left[\sqrt{\frac{2d_C}{\pm R} + 1} - 1\right] \tag{7}$$

$$d_{I,corr} = \mp R\left[1 - \exp\left(\pm\frac{d_I}{R}\right)\right] \tag{8}$$

In these equations R represents the radius of curvature of the ceramic surface which is exposed to the hot gas; d_C and d_I are the layer thicknesses obtained by the plane wall assumption (see eqns (5) and (6)).

In applying the presented relations it is possible to adjust a ceramic component to its thermal load. The level of the ceramic mean wall temperature can be adjusted by the constants in equations (5) and (6), respectively. They have to be set for the adjustment of the layer thicknesses, keeping practicable thickness values and satisfying geometrical constraints and current manufacturing skills.

4 Segmentation

Another alternative for reducing the load of a complex shaped ceramic structure is to subdivide the part into smaller single segments. Firstly, the failure probability, which depends on the component's volume, is not influenced. Only the effect of the created free surfaces reduces the stresses within the components and, consequently, the failure probability. Free surfaces are free of normal stress. Additionally, shear forces between the single segments, which can result from different thermal expansions, are reduced by small relative motions, i.e. under ideal conditions (no friction, free relative movement) unhindered thermal expansion of the single elements is possible.

A further advantage is the increased heat resistance across the contact surface of the elements which leads to a more homogeneous temperature distribution within the elements. Technical surfaces are rough and so the real contact area is significantly smaller than the absolute surface area. This gives rise to drastically reduced heat conduction across separation joints.[9] Hence, the thermal stresses can be reduced. This effect has been examined experimentally by Münz *et al.*[10] He measured the temperature profiles of an axial segmented flame tube made of SSiC. A comparison with finite element calculations revealed that due to surface topology effects the heat resistance is significantly increased across the interfaces leading to smaller temperature gradients in the ceramic.

There are additional advantages of a segmentation. Firstly, the stiffness of the part can be influenced. A separation of stiff areas from more compliant ones leads to a load reduction in the more compliant segments. Secondly, the manufacture of small ceramic components is easier to handle, especially the sintering process, i.e. shrinkage is more predictable which leads to smaller tolerances with less need of machining.

Designers can make use of these effects to control thermal stresses by ingenious segmentation. Areas with different thermomechanical behaviour can be separated, thus obtaining a stress reduction in the individual elements. This principle may be primarily applied to components with significantly varying thermal load or components with areas of contrasting stiffnesses. However, segmentation of a component may increase overall expenditure since every single element has to be fixed in a supporting system. This is not a trivial issue when considering, for example, the required low gap width in combination with the high rotational speeds of turbine rotors. The hybrid construction represents an excellent possibility to bed segmented ceramic components since the whole part is surrounded by an insulation layer supported by the metal casing.[10,11]

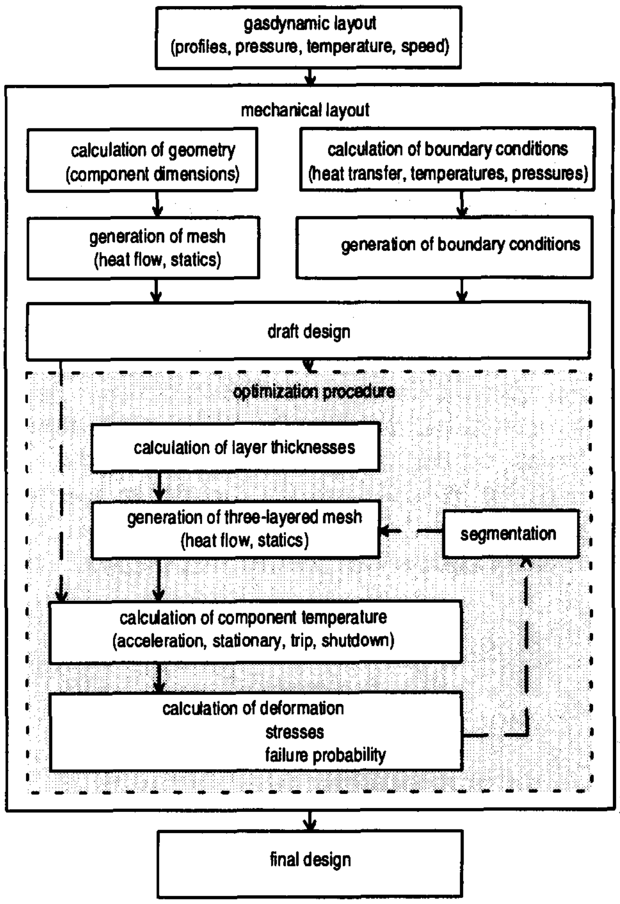

Fig. 3. Design procedure.

5 Methodology

Since the design principles should be applicable to a broad variety of different ceramic gas turbine components, a systematic methodology for the design of thermally high-loaded thin walled parts has been developed. As a first step the gasdynamic layout based on the required gas pressures, temperatures and velocities and a draft design of the component have to be made. This results in a well-defined hot-gas flow channel. Next, boundary conditions and especially thermal loads described by flow-type dependent heat transfer coefficients and gas temperatures can be specified. Taking these data, the local ceramic wall thicknesses and, thereafter, the thicknesses of the insulation layer can be calculated. The metal layer thickness is defined according to the mechanical requirements and, as a result, the optimised hybrid component design is created. The component is segmented if this is recommended by the calculated temperature and stress distribution. A schematic drawing of the procedure, which is partly iterative, is shown in Fig. 3.

To demonstrate the effectiveness of the design criteria two examples, one from a small radial inflow gas turbine[12] and one from an axial gas turbine,[13] have been employed. With the help of finite element calculations two different designs for each component were compared. One represents a conventional design and the other consists of a hybrid wall construction provided with an additional segmentation in the case of the turbine scroll. The material data were taken from sintered silicon carbide (SSiC) since this material has outstanding high-temperature properties and the manufacture procedure is quite reliable even for complicated shapes.

5.1 Example 1: Nozzle guide vanes

To achieve higher efficiency for stationary gas turbines, the turbine entry temperature has to be increased. This means that especially combustor liners as well as the first stage vanes and blades are exposed to high temperatures. To reduce the extent of the need for coolant, most major turbine companies are working on introducing ceramics to the hot-gas path components.[14]

The load-orientated design guidelines were applied to the first stage nozzle guide vanes of a stationary gas turbine.[13] The chord length of the vane is 100 mm and the vane height to chord length ratio is 1·5. An untwisted airfoil with similar endwalls on both ends is considered. Hence, a plane of symmetry at vane mid-height could be implemented and only one half of the vane had to be modelled by finite elements, as shown in Fig. 4.

The thermal boundary conditions which are necessary for calculating the temperature distribution within the body result from the thermodynamic requirements of the Joule–Brayton cycle which give the flow velocities and gas temperatures and, finally, the blade profile. The heat transfer coefficients for airfoil and end–wall are assumed to be a function of both surface coordinates, whereas the main flow temperature varies only with radial position.[15, 16] The heat transfer coefficient on the cool-gas side is set to a constant value of 300 W/m^2K, and the cool-gas temperature corresponds to the compressor exit temperature. Preliminary calculations showed that the mechanical

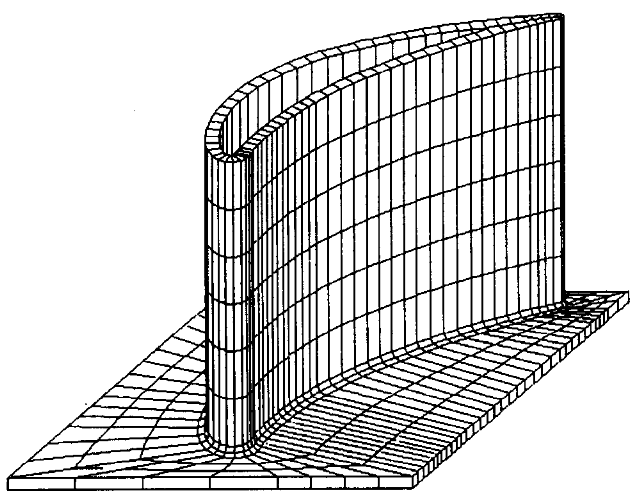

Fig. 4. Finite element model of nozzle guide vane (draft design).

loading, arising from the pressure distribution along the blade's surface can be neglected compared to the thermal stress.[8] This is primarily caused by the fact that the pressure in the cooling channel is of the same order as the pressure in the hot-gas passage.

To demonstrate the advantages of the hybrid construction a directly cooled concept (draft design) was first calculated. The ceramic wall thickness was kept constant at 3 mm. For the total judgement of the ceramic structure, transient working conditions which are typical for a stationary gas turbine were modelled. Therefore, acceleration, loading and shutdown were simulated by changes in the heat transfer and the gas temperature versus the time. Additionally, the thermomechanical behaviour of the airfoil under trip conditions was calculated. This is the critical situation for stationary gas turbines since the temperatures and heat-transfer coefficients change rapidly. The results are plotted in Fig. 5. It can be seen that the maximum principal stresses attain extremely high values especially under stationary conditions. This is due to the high temperature differences in the structure which are typical for the directly cooled concept. A high stress state under stationary conditions is very critical since this is, of course, the predominant load case.

Figure 5 also illustrates the optimised cooled hybrid concept. It is obvious that the application of the new design concept leads to a drastic reduction of stresses. The effect of the three-layered construction with the insulation and the adjusted local wall thicknesses results in a more homogeneous temperature distribution in the part

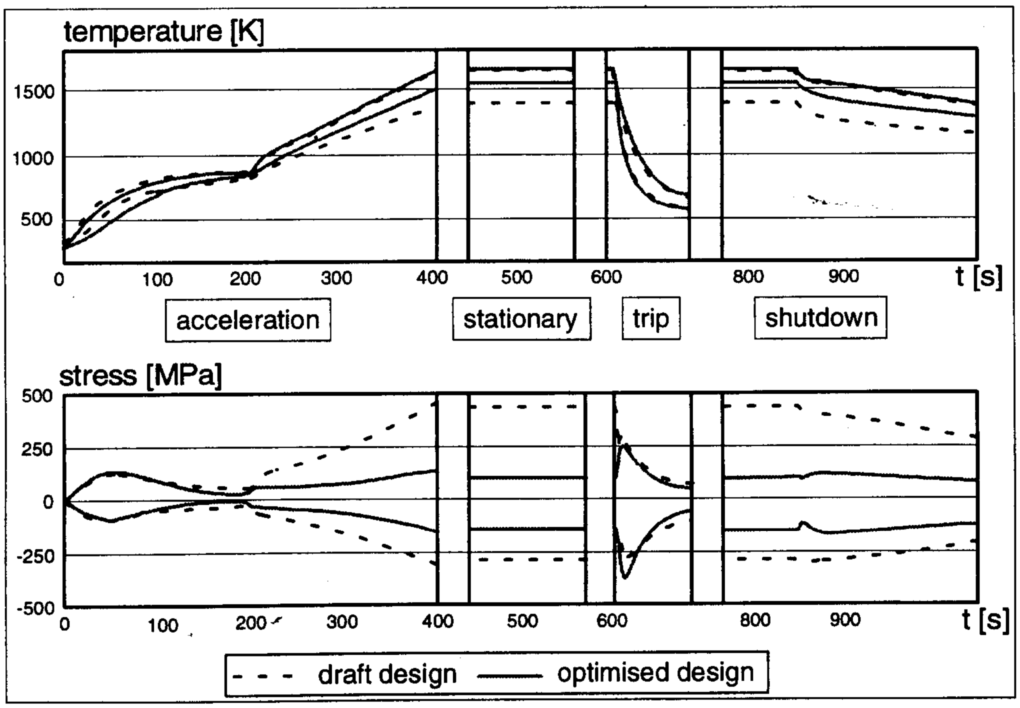

Fig. 5. Maximum and minimum temperature and stresses in the ceramic structure.

Due to the flow's stagnation point, the leading edge of the blade, for example, is thermally high-loaded. In dependency on the high local heat-transfer coefficient h_{hot}, the ceramic wall thickness is increased while the introduced insulation layer is quite thin. Ergo, the temperature differences under stationary and transient conditions could be reduced in this critical region.

For the hybrid concept, trip conditions are most critical. The highest stresses appear at the trailing edge. However, it has to be realized that this region cannot be covered with the optimisation for shell structures. The surface area at the trailing edge exposed to the hot gas is quite large in comparison to the cooled inner surface. Therefore, the cooling is insufficient at this region. The result is that the trailing edge reacts much faster than the shell to changes in the hot-gas temperature, leading to high thermal stresses under trip conditions.

The failure probability calculations obtained with the computer code CERITS revealed an improved reliability. The fast fracture survival probability under stationary conditions for the draft design is zero while the survival probability of the load-oriented designed vane is 99%. Taking subcritical crack growth into account, a time dependent survival probability of 96% for operating 10000 h under stationary conditions is calculated. For trip conditions the fast fracture survival probability is 69%, which clearly demonstrates that these are the most severe conditions.

5.2 Example 2: Turbine scroll

The second example is the volute housing of a small radial turbine. In the low-power range radial inflow turbines have several advantages due to simplicity, costs and performance. Effective cooling requires a high technical and developmental expenditure because of the small size of the components. Hence, ceramics allowing high material temperatures offer great potential for applications in highly efficient small gas turbines.[17, 18]

The first design of the turbine scroll is a monolithic structure with a constant wall thickness of 4 mm. The diameter of the inlet is 56 mm and the scroll diameter is 180 mm. The thermal boundary conditions were obtained in employing correlations for different flow types in spiral casings.[19-21] On the outer surface free convection is assumed. Transient working conditions were modelled by a variation in the hot-gas temperature, whereas there was no distinction between trip and shutdown since there is no controlled shutdown for small engines.

In Fig. 6. the temperature distribution for the draft design under stationary conditions is plotted. This shows a strongly inhomogeneous temperature

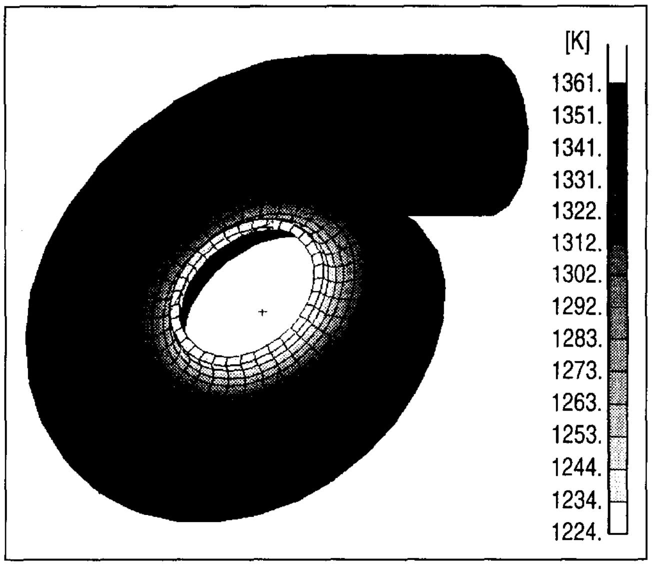

Fig. 6. Temperature distribution of turbine casing under stationary conditions (draft design).

field especially in the shroud region. Here, a reduction in gas temperature takes place due to the enthalpy reduction in the rotor. This gives rise to the high stress state in the housing plotted in Fig. 7. The highest values which prevent a reliable engine operation are reached during shutdown. The loading by inner pressure is neglected since the pressure is quite moderate.

Considering the heat transfer on the hot-gas side, the optimization procedure reveals a three-layered model with ceramic wall thicknesses between 2·7 mm and 7·0 mm and insulation thicknesses between 10·0 mm and 3·0 mm (see Fig. 8). The thicknesses were corrected with eqns (7) and (8), respectively (internally heated pipe). Additionally, a segmentation of the shroud was employed. This is an area with strongly differing thermal loads due to the enthalpy reduction as indicated earlier.[22] Further, the stiffening effect of the shroud could be eliminated. Itoh and Kimura[23] point out that face contact sealing is a simple and effective way to minimize air leakage from the space between ceramic components. Therefore, the two elements: shroud and scroll are assumed to be in flat surface contact. To predict the influence of the contact zones between the segments using the finite element method, the joint had to be modelled. Therefore, a thin interface layer was introduced. With the help of the layer the reduced thermal conductivity could be simulated. The influence of the segmentation on the temperature field in the component could be obtained. For the stress calculation, free relative motion of the single elements was assumed

The stress reduction by applying the design criteria is obvious. Fig. 7 shows evidently that the highest principal stress occurring during acceleration is

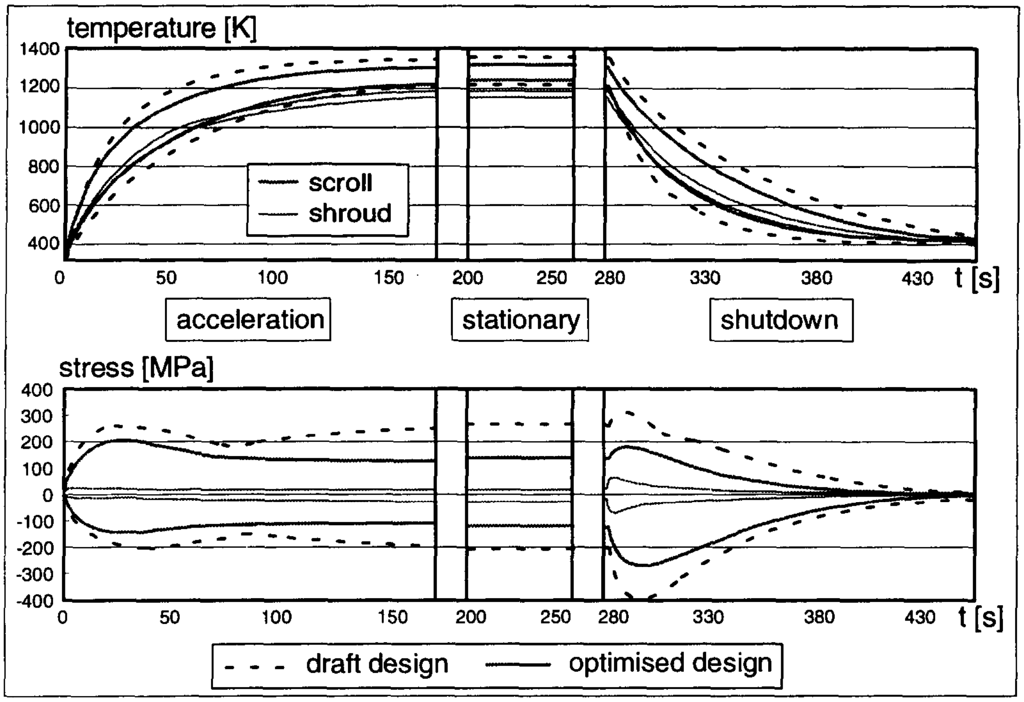

Fig. 7. Maximum and minimum temperature and stresses in the turbine casing.

reduced to 60% in comparison with the highest value in the monolithic turbine casing. The stress value under stationary conditions is reduced to 55%. The drastically reduced temperature differences over the component indicate the more homogeneous temperature in the part. The effect of the separation joint can be seen in the difference between the temperature in the shroud and the temperature in the spiral.

The fast fracture survival probability calculated with CERITS was increased from 12% to 99%. For the optimised design an analysis of the time dependent survival probability, taking subcritical crack growth into account, revealed a value of 22% after 10 h of operating under stationary working conditions. This is not yet sufficient, but the improvement by the application of the simple criteria is clearly visible. Further improvement can be realised by an additional segmentation of the inlet since this is a section that has different thermal behaviour.

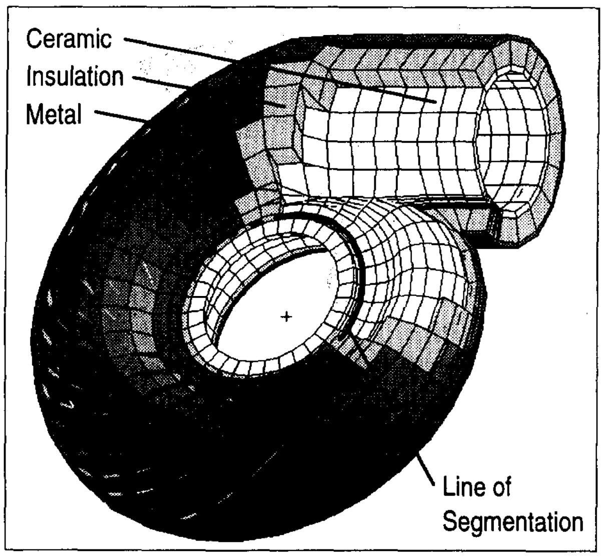

Fig. 8. Three-layered finite element mesh of thermally adjusted turbine scroll (for better visualization of individual layers, some elements are removed).

6 Conclusions

A design methodology for thermally high-loaded ceramic components has been presented considering the typical properties of brittle materials. With the help of an adjustment to the thermal boundary conditions the temperature field in the parts can be influenced. For this adjustment a knowledge of the heat transfer from the hot-gas side of the shell-like ceramic structures is necessary. Considering transient working conditions, the local ceramic wall thickness is calculated first. Thereafter, the insulation thickness can be obtained taking stationary working conditions into account. The three-layered hybrid construction reduces the temperature differences in the components and, therefore, the induced stresses. Segmentation of ceramic parts reveals further stress reduction. The component reliability can be significantly improved.

The development of ceramic nozzle vanes and the turbine scroll requires further work and experimental research to solve the special problems of the individual components. But although, the design guidelines were derived under simplifying assumptions, a drastic stress reduction in the complex shaped parts has been attained. Hence, the effectiveness of an easy applicable tool for the designer was demonstrated. In addition, it has been shown that numerical calculations offer a considerable potential for the preliminary design of ceramic components.

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