Failure analysis and multiscale modeling of thermal barrier coatings

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The transfer of thermal barrier coatings (TBCs) to the high heat flux environment of rocket thrust chambers seems straightforward because TBCs are effectively used in power generation and other aerospace applications. Referring to thrust chambers, TBCs offer great potential to reduce heat flux, coolant temperature and pressure loss; consequently an increased chamber life is expected. A careful design is necessary to cope with the transient boundary conditions, under which TBCs tend to spall, delaminate and crack.

The aim of this work is to address the failure phenomena by experimental investigation and a multiscale modeling strategy. For failure simulation experimental knowledge about the real failure mechanisms is essential. Therefore, copper specimens are coated with a standard TBC coating system by atmospheric plasma spraying (APS) and exposed to thermal cycling. Different cooling agents are used to evaluate the dependence of failure modes on the cooling rate. Delamination of the coatings occurs at the interface between the substrate and the bond coat due to oxide formation of the copper at uncoated edges for fast cooling rates. Under realistic conditions a totally dense coating can not be assured so that failure mode is of importance. No failure was observed in the center of the specimens. Additionally a laser cycling experiment was set up to realize high heating rates and a thermal gradient inside the coating, which led to failure without prior oxidation.

The multiscale modeling strategy is composed of three different scales. A global model simulates a typical thrust chamber at service conditions by means of fluid structure interaction, whereas realistic boundary conditions are extracted from critical design regions. These boundary conditions are applied to a macroscale model to analyse possible TBC delaminations. To complement the modeling strategy, a microscale model is used to evaluate critical stresses at the interfaces.

1. Introduction

The wall of modern liquid rocket engines is exposed to extreme thermal loadings. The combustion gases reach a temperature level of about 3,600 K with a chamber pressure of up to 20 MPa [1]. The generated heat flux reaches its maximum with 131–147 MW/m² at the throat region [2]. In present applications high aspect ratio cooling channels are milled into the copper liner, while the chamber wall is approximately 1 mm thick. The cryogenic fuel is typically pumped through the coolant passages along the combustion chamber liner. This setup stays intact only for a few engine cycles, because the uncoated
A copper alloy fails by a combination of creep and low cycle fatigue. In literature this failure mode is referred to as the so-called "dog-house"-effect [3].

A protection of the thin copper cooling structure is a promising strategy to enhance thrust chamber life. Thermal barrier coatings are widely used in applications with elevated temperatures involved, e.g. gas turbines and aero-engines. Therefore, this concept is transferred to rocket engine applications. Although the thermomechanical loading conditions differ, the main requirements of a thermal barrier coating are thermal and oxidation protection. Different coating systems have been considered in recent research. A thermal barrier coating system consisting of a NiCrAlY top coat and a Cu-Cr bond coat on Cu-8Cr4%Nb-substrate has been investigated by Raj et al. [4, 5]. These coatings were cold-plasma sprayed and hot-isostatic pressed and showed good adhesion in first thermal cycling tests. A TBC-system consisting of a MCrAlY-bond coat and zirconia was applied by electron beam vapor deposition by Schulz et al. [6].

In this research a standard TBC coating system is used to gain more understanding on failure modes on a copper substrate. It is applied by atmospheric plasma spraying as this is a method which can easily be applied to big components without need of vacuum. After successfully adapting spraying conditions to the new substrate, well-adhering coatings can be applied [7]. Because loading conditions and substrate materials are different, the known failure modes from TBCs in gas turbine applications [8] cannot be transferred and need to be investigated experimentally to provide a realistic basis for simulation. Therefore, cycling experiments with different conditions were performed.

Because of thermal mismatch of the different coating layers, stresses that are located directly at the interfaces are important to understand different failure modes. To account for this, an existing micro-model of the microstructure [9, 10] was adapted to the new substrate, and cooling stresses are evaluated and compared to the experimental results.

In addition to the experimental investigation of TBC systems, this work uses a global fluid-structure interaction approach to predict inservice conditions of a TBC protected cooled rocket thrust chamber. While in the first year of the investigations several parametric studies have been performed to understand basic phenomena of the delamination of thermal barrier coatings and how to model them [11], the following work is focused on more realistic loading and boundary conditions. The fluid-structure interaction problem of the global model presented in [12] is extended to find more realistic conditions for a TBC protected combustion chamber liner. This input is used for the macroscale delamination model of the present work and will also be applied to the microscale model in subsequent analyses.

The main focus of the present work is to understand possible failure mechanisms and, consequently, to develop a simulation tool for optimized TBC design.

2. Experimental results

To understand the failure of thermal barrier coatings on copper substrates, a good experimental knowledge of the real failure mechanisms is necessary. Due to the difference in materials' properties of copper- and nickel-based alloys and to the difference in loading conditions, it is not clear whether the known failure mechanisms of thermal barrier coatings in gas turbines [8, 13] can be transferred to rocket engines. Therefore, state-of-the-art thermal barrier coatings were applied to copper samples and exposed to thermal cycling to investigate possible failure mechanisms.
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2.1. Materials and coating system

Due to its good high temperature properties, the commercial alloy CuCr1Zr (specification number 2.1293), which is an age-hardenable copper alloy containing 1% chromium and 0.3% zirconium [14], was chosen as substrate material. A standard coating system known from gas turbine applications was applied by atmospheric plasma spraying (APS) to the specimens. It consists of a NiCrAlY bond coat (Ni-22%Cr-10%A-1%Y) and a partially stabilized zirconia (8% yttrium oxide) top coat. The coating parameters were optimized for the new substrate material [7], resulting in a well adhering coating.

2.2. Thermal cycling experiments

Thermal cycling experiments were performed on flat specimens with dimensions of 35mm x 30mm x 5mm. The specimens were completely coated from one side while the other five sides remained uncoated. The cycling experiments were performed to assess the adherence of the produced coatings and to learn about failure mechanisms that may occur.

The specimens were heated up to 800°C inside an oven, and, after a holding time of 30 minutes, they were cooled down in a cooling agent outside the oven. This cycle was repeated at least 50 times on each specimen in case of no failure of the coating system.

The described cycling method is "isothermal" in the sense that all parts of the coating and the substrate are at the same temperature at the same time and are cooled and heated more or less simultaneously. No thermal gradient is applied to the coating. Nevertheless, due to the difference in the coefficients of thermal expansion, large thermal strains are imposed during heating and cooling of the specimen, which could lead to a spallation of the coating.

The specimens were optically inspected after each cycle and after each 5-10 cycles one specimen was taken from the experiment for metallographic preparation. The prepared samples were investigated by optical microscopy as well as by scanning electron microscopy (SEM).

2.2.1. Dependence on cooling rates

In pilot testing it was found that the behaviour of the coatings depends on the cooling rate [15]. For this reason three different cooling agents were used: air, icy water and liquid nitrogen (LN₂). Air cooling shows the slowest cooling rate with about 0.5 K/s from 800°C to room temperature. The fastest cooling rate, 13 K/s from 800°C to 10°C, is
reached with icy water. Liquid nitrogen shows an in-between value with 7 K/s from 800°C to -140°C. Cooling with liquid nitrogen was applied because it reaches a temperature which is nearly comparable to liquid hydrogen that is used in real application, although due to gas formation at the surface of the specimen the cooling rate is not as fast as in icy water.

Specimens that were cooled down slowly (air cooling) did not show any failure of the thermal barrier coating after 50 cycles. A micrograph of a sample after exposure can be seen in Fig. 1. At the uncoated edges the copper oxidates severely but the coating itself seems to provide a certain oxidation protection. No spallation or partial delamination of the thermal barrier coating was observed with this cooling rate.

At higher cooling rates (icy water and LN$_2$) some of the specimens behaved similar to those cooled down slowly and did not show any sign of failure. Other samples showed partial delamination at the interface of the substrate and the bond coat (compare Fig. 2). A layered structure of copper oxide formed at these delaminated regions. Delamination started only at the uncoated edges where the copper oxide undermines the coating. Statistical variations of the coatings are believed to be the reason why this phenomenon is seen only in part of the samples. This failure mechanism is critical under operational conditions because a totally dense coating can not be assured due to erosion. This mechanism is mainly driven by oxidation of the substrate, and none of the coatings failed completely.

2.2.2. Oxidation behaviour

All tested specimens show severe oxidation at the edges which is not surprising. The bond coat seems to provide oxidation protection to the underlying substrate, but SEM analysis shows an inner oxidation at the grain boundaries of the substrate. The inner oxidation starts at the interface between bond coat and substrate. A SEM-micrograph of an etched sample after 50 cycles (LN$_2$) is shown in Fig. 3. Energy dispersive X-ray analysis spectroscopy (EDS) shows that chromium oxide has formed at the grain boundaries. This confirms that the bond coat has a permeability for oxygen either through diffusion or direct contact. In Fig. 4 typical SEM micrographs before and after exposure to cycling are shown. A low accelerating voltage (5 kV) was used to show porosities and surfaces more clearly. Due to sintering of the zirconia at high temperatures, the top coat is denser after exposure. The bond coat is relatively dense before cycling, but shows some porosity after cycling which might lead to a better permeability for oxygen and
therefore worse oxidation protection. It is not quite understood why this porosity forms during exposure, but interdiffusion effects might be the reason. For providing necessary oxidation protection this issue needs to be investigated in detail in the future.

2.3. Laser cycling experiments

2.3.1. Set-Up

To account for the high thermal gradients in real service, a different testing method than thermal cycling is needed. Heating the samples only on one side by a laser is an approach that has already been practiced in the past [16–18]. For the pilot testing a Nd:YAG laser system developed at the Federal Institute for Materials Research and Testing (BAM) in Berlin with 1.5kW maximum power was used. The laser beam is moved spirally from the center of the specimen to the outside margin. The local temperature is recorded with a high speed IR-camera. This method is normally used to investigate thermal shock properties of ceramics, but is used in the present study to produce a thermal gradient in the coated specimen [19]. To ensure good absorption the TBC was treated with a Fe$_3$O$_4$ powder suspension before testing.

The pilot tests show promising results, but the good heat conductivity of the copper lead to an inhomogeneous temperature distribution on the sample. Therefore, a new set-up was built using a diode laser with 3kW maximum power and a very broad focal point, which is shown in Fig. 5. With this new set-up the whole specimen is in the focal point and the laser beam is not moving. The surface temperature is controlled by a high speed pyrometer.

2.3.2. Results

Pilot tests have been performed so far. Fig. 6 shows a typical failure after laser cycling. The thermal shock induced by the laser leads to a delamination of the whole coating at the substrate interface. Due to the large difference in thermal expansion coefficients of the bond coat and the substrate, large thermal stresses were probably induced in this region. The first results show on the one hand that, again, the substrate interface is the weak interface and on the other hand that the laser heating method is a suitable method to qualify different coating systems because it produces damage by thermal stresses.
3. Microscale finite element simulation

3.1. Model geometry

To understand the possible failure mechanisms and stress states at the microscale, an existing finite element method (FEM) model [9, 10] was adapted to the new substrate. The model geometry (Fig. 7) is a solid cylinder that is infinitely extended in its axial direction. The substrate has a radius of 10 mm, the bond coat has an average thickness of 80 $\mu$m, and the top coat has an average thickness of 120 $\mu$m. Both interface regions are modeled with a sinusoidal geometry. The amplitude of the sine waves is modified for the analysis.

The model is constrained in the axial direction on the $y$-axis. The nodes at the bottom of the model are constrained in the axial direction, while the movement of the nodes on the top of the model is constrained such that all these nodes must have the same vertical displacement. Therefore, the model can be considered as a slice taken out of a sample that is very long and unconstrained in the radial and axial direction.
The model is cooled down from 800°C to room temperature (20°C). A stress-free state is assumed at high temperature because of the residual stresses in the coating after plasma-spraying at room temperature [20]. The cooling is performed isothermally which means that all the nodes change their temperature at the same time. Because we assume high cooling rates, only elastic stresses are evaluated and no plasticity such as creep is taken into account.

Two different substrates are compared: a nickel based superalloy commonly used for application in gas turbines and a copper substrate used in rocket applications. Material data is taken from [21], [14] and [22].

To account for a variation of surface roughness, the amplitude of the sine waves is modified from 0.1\(\mu\)m to 4.5\(\mu\)m. In reality these values are dependent on the grain size of spraying powder and on the used powder for sand blasting in case of the substrate interface. Fig. 8 shows a typical micrograph of an interface between substrate and bond coat with a roughness in the analysed range.

Elastic cooling stresses in radial direction (S11) are evaluated depending on the surface roughness. The values of peak and valley position (compare Fig. 7) of each coating layer at the two interfaces are analysed. Two different analysis for the two substrate materials are compared in the following.

3.2. Analysis of cooling stresses

In Fig. 9 radial cooling stresses (S11) at the interface of thermal barrier coating and bond coat are shown for the simulation of a coating on a copper substrate and for a coating on
a nickel-base substrate. The main difference of the material parameters is the coefficient of thermal expansion (CTE), which has a value of $16.3 \times 10^{-6} \text{K}^{-1}$ for copper and $12 \times 10^{-6} \text{K}^{-1}$ for Ni-base substrate. It is evident that the CTE has an important influence on the stress state. The stress state on the right-hand side of Fig. 9 is similar to the situation known for TBC systems on nickel-based substrates without TGO [8]. Compressive stresses are located in the valley of the sinusoidal interface while tensile stresses are located in the peak position. The stress state is governed by the thermal mismatch between thermal barrier coating and bond coat.

The simulation of coating on a copper substrate (left-hand side of Fig. 9) shows a different situation. The maximum stresses have shifted away from the interface towards the bond coat. The stress state is no longer only governed by the thermal mismatch of bond coat and TBC, but the thermal mismatch between bond coat and substrate causes an axial compression which also influences the stress state in radial direction. This effect is explained in [23] in more detail. This change in stress state fits to the findings of laser cycling experiments, where failure occurs at the interface between the substrate and the bond coat instead of the other interface which is vulnerable for Ni-based substrates.

Fig. 10 shows the radial cooling stresses at the bond coat/TBC interface depending on the amplitude of the sine wave. With a higher amplitude the stresses increase and the absolute difference between the two simulation becomes even greater.

To verify the assumption that stresses are higher at the substrate/bond coat interface in case of the copper-based substrate, this interface is evaluated. In Fig. 11 radial cool-
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The stresses (S11) at the interface of thermal barrier coating and bond coat are shown for the simulation of a coating on a copper substrate and for a coating on a nickel-based substrate. As expected, the stresses at this interface are significantly higher for a copper-based substrate as the stress state is governed by the CTE-mismatch between substrate and bond coat. Fig. 12 shows an even larger difference between the maximum radial cooling stresses for the two cases at this interface. For a copper-based substrate, the stresses reach values up to 200 MPa for compressive and tensile stresses while the stresses for a Ni-based substrate are significantly lower. This fits well to the experimental findings and leads to the assumption that the failure mode is quite different from those common for gas turbine applications and an important issue will be the optimisation of the substrate/bond coat interface in the future.

4. Fluid-structure interaction analysis

Contrary to monolithic approaches, where the complete physics of the coupled problem is solved with a single code, the partitioned formulation of numerical coupling uses individual codes for the fluid and structural analysis. This is a common approach because the single field codes are well-established and provide a variety of specialised and valuable modelling features. The simulation environment ifls used in this study provides a framework to simulate coupled phenomena in a partitioned formulation. Detailed information about the realized numerical coupling concept can be taken from [24]. In this work the fluid domain is analyzed by the DLR TAU-Code [25], which is an unstructured RANS solver based on the finite volume method. The structural domain is analyzed by the multi purpose finite element code ABAQUS.

Fluid-structure interaction (FSI) analysis of the involved domains hot gas, structure and cooling fluid is computational expensive. Computational cost can be reduced by applying symmetry conditions in the different computational domains. For the FSI analysis the coupled domains of the rocket thrust chamber are modelled by a 3D parametrized approach at which the assumption of periodic repetition is applied. A detailed description of the parametrized approach is presented in [12, 26]. The contour of the structural model can be taken from Fig. 13(a). The parametrization extends from the thrust chamber contour and cooling channel design to the CAD modelling and finally to the spatial discretisation of the involved domains. For this work the parametrized cooling channel structure of [12] is upgraded with a TBC representation shown in Fig. 13(b). The hot gas domain is modelled by means of the finite volume method and the structural domain by means of the finite element method. The element formulation for the cooling channel structure consists of 8-node continuum shells for the TBC system (BC, TBC) and 8-node solids for the copper and nickel alloy. Material parameters of copper, BC and TBC are taken from [14, 21, 22]. INCONEL alloy 600 [27] is used for the nickel jacket of the combustion chamber.

Extracted general parameters of a 40 kN LOX/H₂ subscale rocket thrust chamber defined by Astrium Space Transportation GmbH, Propulsion & Equipment serve as input for the parametrized modelling approach. The thrust chamber features 80 cooling channels in the combustion chamber and 160 cooling channels in the nozzle extension. The TBC system of the present FSI analysis consists of 30 μm bond coat and 10 μm top coat.

The FSI analysis considered in this work is assumed to be steady state for all involved domains. A two way coupled formulation described in detail in [12] simulates the heat transfer problem between the hot gas and the cooling channel structure. A subsequent
A sequentially coupled thermal-stress analysis is performed to compute the structural response in a hot gas run. The computed results of the highly loaded critical throat region serve as boundary condition for the macro scale delamination model, which will be presented in the next section. For the hot gas analysis finalized combustion is assumed, whereas the preliminary design tool RPA (Rocket Propulsion Analysis) [28] was used to compute the thermochemical species reactions. The results of RPA served as input for the steady RANS analysis assuming ideal gas law. Assumed boundary conditions and the applied numerical coupling scheme can be taken from [12].

In Fig. 14 cut views of the converged temperature distribution are shown. The critical region is identified at the nozzle throat as expected. The temperature rises up to 1600 K on the hot gas facing surface, whereas 810 K are reached on the surface for the uncoated thrust chamber analyzed in [12]. The thermal barrier effect of the TBC system provides a temperature drop up to 495 K on the bond coat substrate interface.

5. Macro scale delamination modelling

Aside from erosion problems investigated by Quentmeyer et al. in [29] it was shown by Miller and Lowell in [30] that TBCs are prone to delamination at the interfaces and even ultimate failure by spallation phenomenon.

The failure phenomenon investigated here includes the effect of macroscopic delamination of TBC systems in rocket thrust chambers. Macro scale delamination modelling is well established in the field of fibrous composites, however, in the field of TBC systems applied to rocket thrust chambers macro scale delamination growth was not studied so far. In the case of buckling of the sublaminates in the area of the delamination, which will result in a considerable Mode I part (opening mode), it makes sense to use a Fracture Mechanics (FM) approach. For FM approaches an initial delamination must be present at which the crack tips are used to determine the fracture mechanical data. An assumed initial macro scale delamination may have an impact on the propagation behaviour, which must be studied in future. In future studies initiation of macro scale delaminations could be derived from the micro scale FEM analysis presented above.
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Delamination propagation analysed by a FM approach follows directly from the energy release rate $G$ computed by means of linear elastic fracture mechanics for a given loading compared to the critical value $G_c$. The fracture energy $G_c$ is a material property and consequently independent of the loading. Several methods were proposed and validated to compute $G$ or respectively its modal components $G_I$ and $G_{II}$, e.g. J-Integral, Virtual Crack Extension, Virtual Crack Closure and Williams [31–34]. Applicability of these methods in the context of TBC systems shall be investigated in subsequent studies of the present work.

The present work emphasizes the formulation of a generic 3D parametrized modelling approach by means of FEM, which will serve as base for future sensitivity analysis with respect to delamination propagation under in service conditions.

5.1. The parametrized 3D model

The parametrized 3D delamination model presented in this work consists of the TBC system setup mentioned above. The basic setup of the implemented model consisting of a substrate and the extremely thin layers of bond coat (BC) and top coat (TBC) is shown on the left of Fig. 15. The parametrized approach is modelled via the preprocessor ABAQUS/CAE. The initial delamination is idealized by the ellipse equation. The special case of a circle can also be chosen as can be seen on the left of Fig. 15. For this work a continuum shell formulation of 8 nodes is chosen for the thin coating layers BC and TBC, and the substrate is analysed by 8 node solids.

In case of ideal structures the local buckle phenomenon of the sublaminates can cause numerical solution difficulties. In order to countervail this effect a small imperfection can be introduced in the area of delamination, which may also be seen as a realistic effect caused by oxides. The out-of-plane global coordinates inside the delami-
nation area are superimposed with a half cosine wave parallel to the local $\xi$, $\eta$ coordinate system:

$$\Delta z = h_i \cos\left(\frac{\pi}{2a} \xi\right) \cos\left(\frac{\pi}{2b} \eta\right), \quad b = b \sqrt{1 - \frac{\xi^2}{a^2}} \quad \text{within} \quad \left(\frac{\xi}{a}\right)^2 + \left(\frac{\eta}{b}\right)^2 < 1, \quad (5.1)$$

where $h_i$ is the maximal imperfection, and $a$ and $b$ are the major and minor semiaxes. This expression assures a tangential plane at the crack front between the intact TBC system and the delamination itself.

Furthermore, the parametrized model features variation in delamination position and orientation according to the global specimen. Multiple delaminations with individual interface positions substrate – BC or BC – TBC are possible as displayed on the right-hand side of Fig. 15. Elliptic representation in parametric coordinates allows for automatic spatial discretisation enhancement in areas of large curvature.

### 5.2. Numerical analysis

A first steady state fully coupled thermal-stress analysis is performed with the ABAQUS FE Software. The analysis is performed taking large displacements into account. Global dimensions of the parametrized specimen, shown in Fig. 16(a), are extracted from the thrust chamber FSI analysis of section 4. The height $h_{Cu}$ equals the substrate wall thickness and $b$ equals the width of one combustion chamber cooling channel. For simplicity the length $l$ is chosen to equal $b$. The parameters are listed in table 1. The TBC system equates the setup of the static heat transfer FSI analysis. One initial delamination is defined with major and minor semiaxes of $150 \mu m$ and $100 \mu m$. The maximal imperfection height is chosen to be $5 \mu m$. A cut view in the $x,z$ plane of the discretised imperfection is shown in Fig. 16(b). The initial delamination is located in the middle of the specimen.

Thermal and mechanical boundary conditions are extracted from the global FSI analysis. In the global analysis the cooled nickel outer jacket generates a compression load acting on the copper substrate, which is deformed towards the inner radius. The transfer from global to local boundary conditions is sketched in Fig. 17, in which the thermal and mechanical boundary conditions are defined. Material properties of the substrate and the TBC system are the same as mentioned above.
The temperature profile of the present analysis is shown in Fig. 18. It is shown that in the detailed analysis the high thermal conductivity of the copper substrate leads to an almost constant low temperature of the substrate. A high thermal gradient is generated through the thin TBC system. The close view of the delamination temperature profile shows the impact of the gap, whereas the temperature rises up to about 1300 K in the bond coat region. The substrate facing the gap is not heated because this analysis does not include radiation effects so far. It is expected that radiation will have an effect on the thermal loading of the crack front, wherefore this will be analysed in following studies.

The deformed state is shown by a cut view in Fig. 19. The relative bulging of the delamination is 2.26 μm for the 5 μm imperfection. In a subsequent analysis the imperfection height was increased to 10 μm, at which the relative bulging was computed to be 3.9 μm. Further sensitivity analysis of the discretisation influence have to show if increasing imperfection height decreases relative bulging proportionally as implied by the present analyses.

6. Conclusions and Outlook

Failure analysis and multiscale modeling of thermal barrier coatings in context of cooled rocket thrust chambers were presented. The experimental investigation of a typical gas turbine TBC system applied to a copper-based substrate has shown that the failure mechanisms differ compared to gas turbine applications. Thermal cycling led to partial delamination due to copper oxide formation only at specimen edges for high cooling rates. This failure mode is critical in case of a damaged layer e.g. due to erosion in...
service. No spallation of the coatings occurred in thermal cycling. To account for the thermal gradient inside the coating and fast heating rate, a laser cycling experiment was set up to qualify different coating systems. First experiments show delamination interface between substrate and bond coat. This failure mechanism will be investigated in subsequent studies. The microscale finite element analysed elastic cooling stresses at the two interfaces of the coating system. At the bond coat/substrate interface high-
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FIGURE 19. Cut view in the y plane of the analyzed imperfection.

Est tensile and compressive stresses were detected which matched the experimental findings in laser cycling experiments.

A steady fluid-structure interaction analysis was performed on a cooled rocket thrust chamber in order to predict realistic loading and boundary conditions for the detailed analyses. First thermomechanical analyses with extracted boundary conditions of the global model were performed on the presented generic parametrized 3D delamination model. This macroscale approach will serve as base to analyse the phenomenon and sensitivity of delamination propagation in subsequent analyses.

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References


