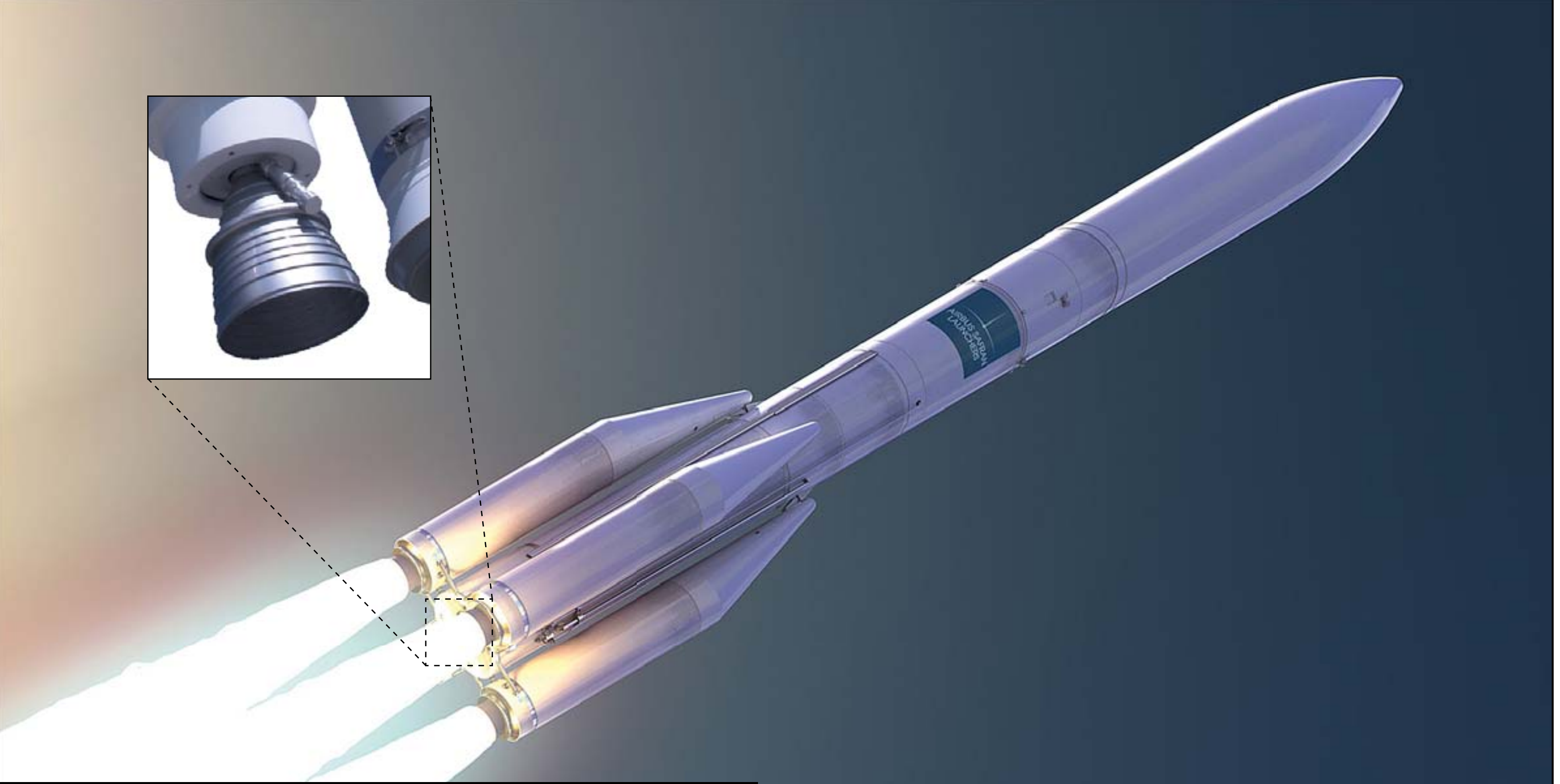

TMF PANEL OPTIMIZATION

Ariane Group GmbH developed a simulation procedure in order to reduce the effort on full scale hardware testing. optiSLang was used for parameter identification and optimization of Thermo-Mechanical Fatigue (TMF) panels representing in design and size one part of the combustion chamber of the Ariane 6 European launch vehicle.

Introduction

The propulsion system of a launch vehicle produces thrust in order to lift off and accelerate a carrier rocket into orbit. According to the principle of action and reaction between the combusted reaction gases and the launch vehicle, the acceleration depends on mass and velocity of the emitted matter. To keep the required fuel mass consumption low, a high exhaust velocity is desirable, which in turn requires high pressure levels and hot reaction temperatures inside the combustion chamber. Different concepts are available for the combustion chamber to maintain structural integrity. Here a regenerative cooled combustion chamber is considered, where a cryogenic fluid is fed through cooling channels in the combustion chamber hot gas wall.

Fig.1 shows a combustion chamber with its typical sandwich-like cooling channel structure. It is composed of an inner liner, typically made of a copper alloy, and the outer high-strength jacket, responsible to carry external loads. The hot gas wall as the innermost part of the liner represents the most loaded part of a combustion chamber. It is exposed to large temperature gradients between the combusting medium with up to 3000 K and the cryogenic coolant with around 40 K. The damage behavior of the hot gas wall is intended to be reproduced by the TMF panel tests by using specimen of equal cooling channel geometry and by applying loading conditions similar to those inside the combustion chamber.

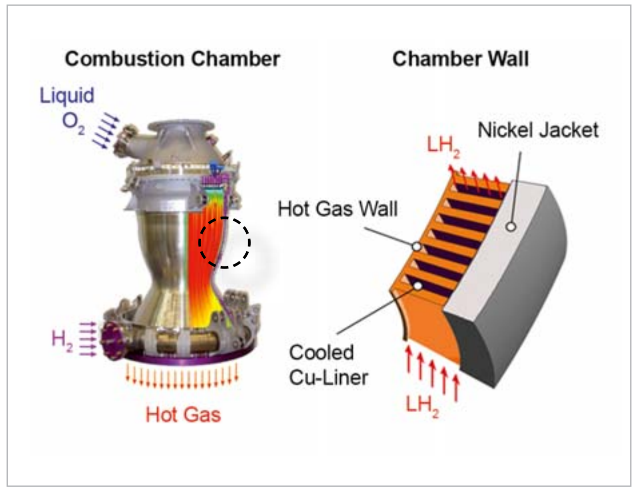

Fig. 1: Functionality of the launcher's main engine with enlarged part of the cooling channel structure of the engine's chamber wall

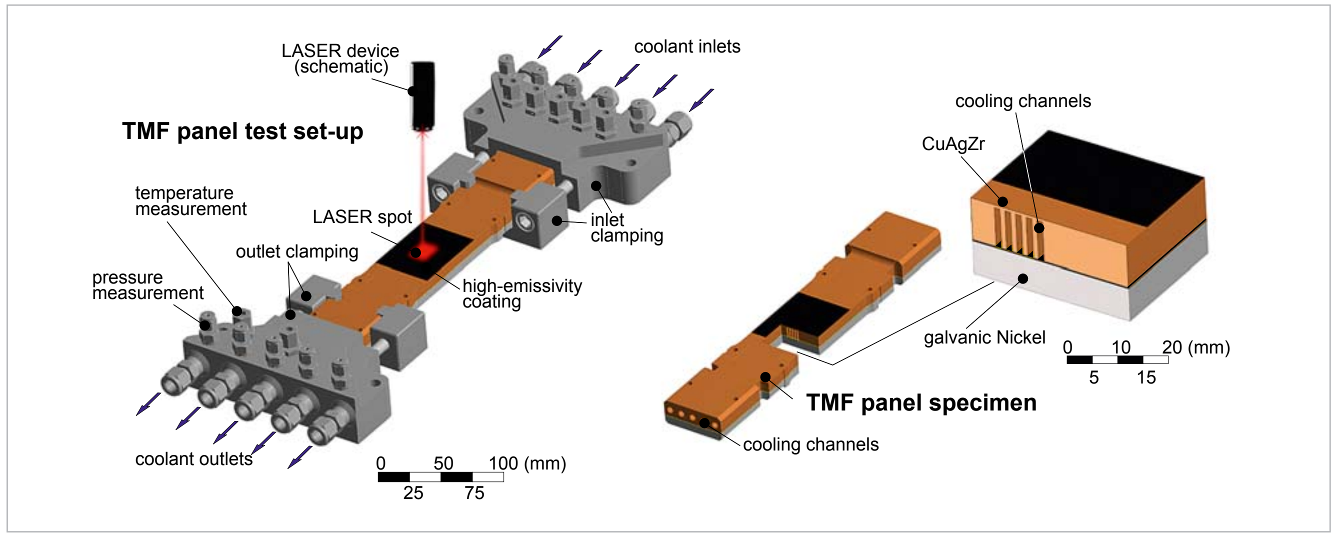

Fig. 2: TMF panel design and test concept [5]

TMF panel test

The TMF panel was created considering two goals. First, for the validation of the damage model, which was created for lifetime predictions on the hot gas wall. A detailed description of the damage model formulation, which accounts for the viscoplastic material behavior, ageing and damage effects under TMF loading conditions, can be found in [5]. With the TMF test, the model is applied to a more complex structure than for the specimen of tensile, fatigue and creep tests in order to justify its applicability on flight hardware. Based on the validated material damage model, a justification capability of today's combustion chambers is provided. Second, panel based TMF testing has the potential to be used in the development process of new combustion chambers as a cost efficient alternative to full-scale tests to investigate the capabilities of new materials or designs. With this intention, this article focuses on the representativeness of the panel's damage behavior compared to the combustion chamber hardware.

TMF panel design

As depicted in Fig. 2, the TMF panel is manufactured out of the liner material CuAgZr that includes five cooling channels in the dimensions of the combustion chamber. On its backside, a Nickel layer is applied by the galvanic deposition process.

In order to generate the high heat input into the panel's hot wall, a 10kW laser device is used to produce a heat flux of approx. 20 MW/m² on the panel surface. Due to the low absorption capacity of the panel material, the laser loaded surface is covered with a high emissivity coating. Further, a nitrogen flow is established that represents the regenerative cooling of the original combustion chamber structure. The pressurized liquid nitrogen circulates through the five cooling channels of the copper alloy part and cools the structure down to keep the hot gas wall temperature at a certain level. A more detailed description of the test stand can be found in [4].

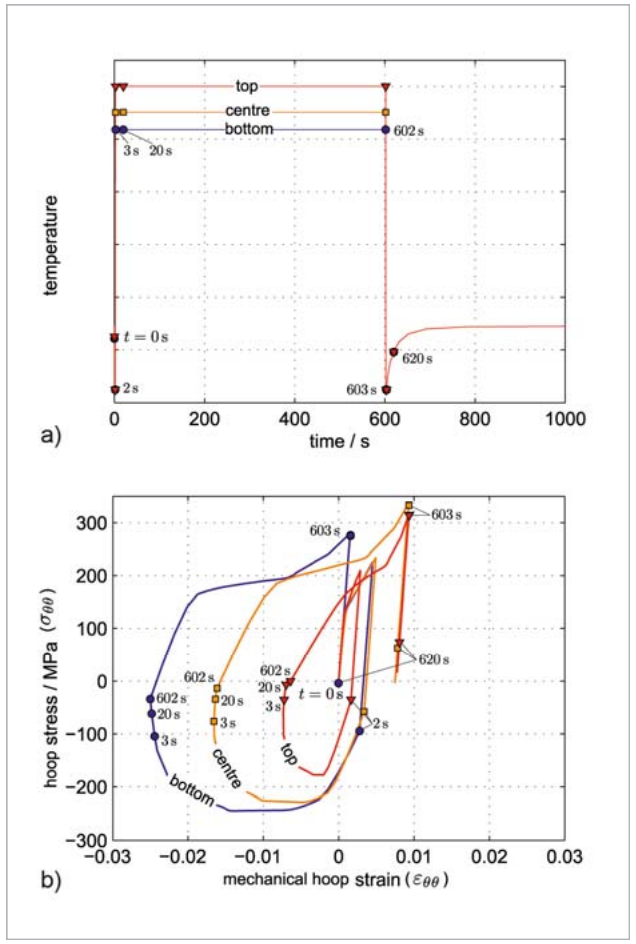

Fig. 3: Stress strain hysteresis in the hot wall ligament during the first load cycle: a) Transient temperatures; b) Stress-strain response in different locations through the liner ligament [5]

Comparison of combustion chamber and panel damage behavior

During a typical load cycle, the combustion chamber is first pre-cooled, which leads to circumferential contraction. Since the liner material usually has a higher coefficient of thermal expansion than the jacket material, a tensile stress is induced within the hot gas wall during the first two seconds as depicted in Fig. 3b. After ignition, the liner material heats up while the cooled jacket prevents the liner to expand. Hence, a compressive stress state occurs in the hot gas wall that leads to inelastic deformations of the copper material throughout the hot run time of 600s. Once the engine is shut down, a post-cooling phase starts leading back to a tensile stress state. Finally, the temperature returns to an ambient level.

Multiple load cycles of precooling, hot run, post-cooling and return to ambient levels stresses the structure in a domain that is known as thermo-mechanical-fatigue (TMF). These load conditions lead to thinning of the hot gas wall which tends to a roof shaped configuration known as the dog house effect as depicted in Fig. 4b. Microstructural investigations

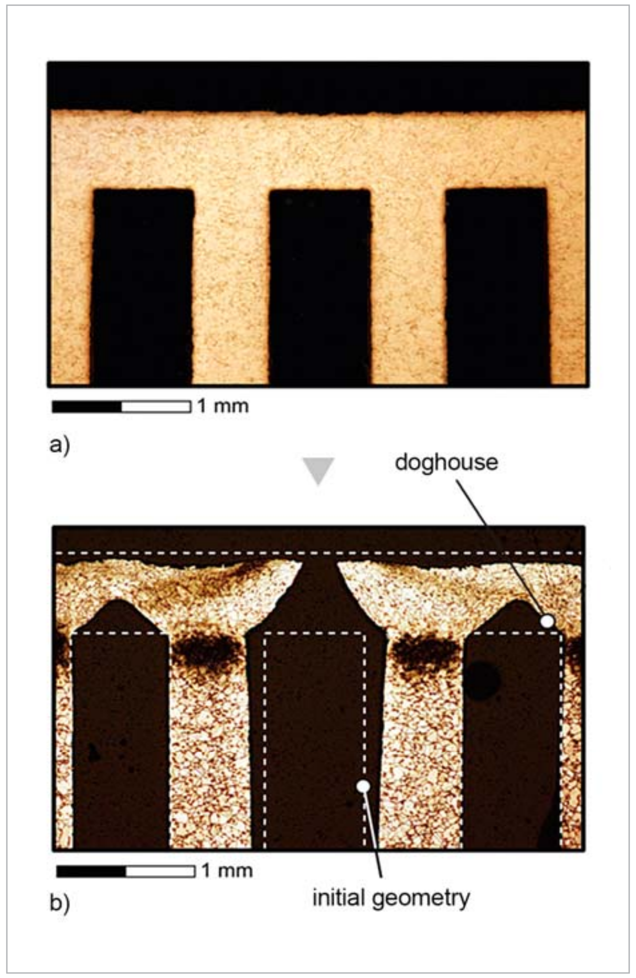

Fig. 4: Shape of the cooling channel structure inside the combustion chamber: a) initial state; b) after hot firing campaign [5]

confirm that ductile damage mechanisms lead to microdefects. During further load cycles, they extend towards macroscale defects. Hot gas wall failure occurs with the creation of macro cracks at the tip of the doghouse as seen in the middle cooling channel of Fig. 4b. Such a crack is not critical for the integrity of the entire engine but still shall be avoided.

On the local stress-strain level, the thinning of the hot gas wall corresponds to a circumferential tensile strain, which accumulates from cycle to cycle. In this case, the stress-strain hysteresis is open in the direction of positive hoop strain, see Fig. 5a.

Looking at the behavior of the TMF panel, it occurs that the stress strain hysteresis differs from what is seen in the combustion chamber, see Fig. 5b. During post cooling, the stress

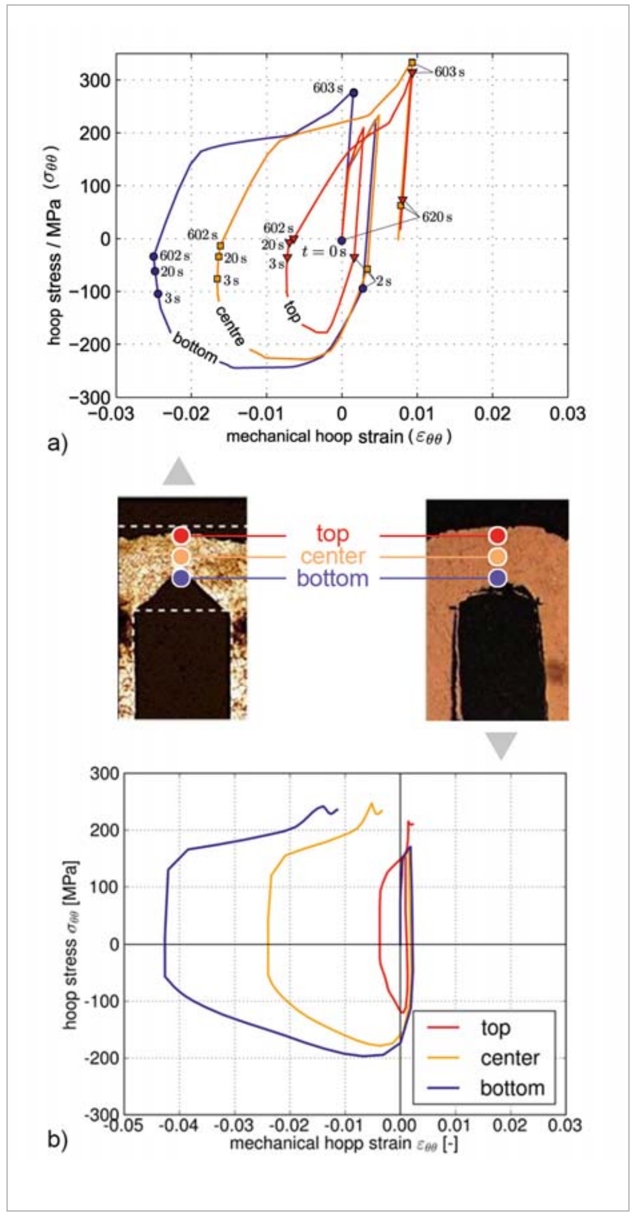

Fig. 5: Stress strain hysteresis in comparison between a) combustion chamber and b) TMF Panel

state is similarly in tension, but the strains get stuck in the compressive domain. As a result, the laser loaded wall of the panel is thickening in contrast to the thinning of the hot gas wall in the combustion chamber. This changes the damage conditions and reduces the representativeness of the panel tests.

In order to achieve a damage behavior in panel tests that is similar to the one found in a combustion chamber hot firing cycle, it is necessary to move the mechanical strain state after post cooling to the tensile domain. Former investigations revealed potential improvements by the adaption of test process parameters, like laser heat input or cooling mass flow, but their implementation on the test were limited. Therefore, further potential for improvement is now investigated on the geometrical level.

Optimization approach

The optimization with optiSLang is based on an ANSYS simulation that delivers the strain response for the designs under investigation. Therefore, a parametrized APDL script (ANSYS Parametric Design Language) is used to create the geometry, build the model, apply the boundary conditions, launch the job and extract all necessary result data. Finally, an error value is returned to optiSLang for each design point. Its minimization corresponds to the evolution towards the best design.

Geometry parameters

Fig. 6 shows a cut through the panel being under investigation. The illustration gives an overview of the design parameters that are modified by the optimizer. Similar to the original design as shown in Fig. 2 (see page 31), the panel consists of a copper liner, a nickle jacket and includes five cooling channels. As a conceptual novelty to the former flat panel design, the current study includes the assessment of curved panels.

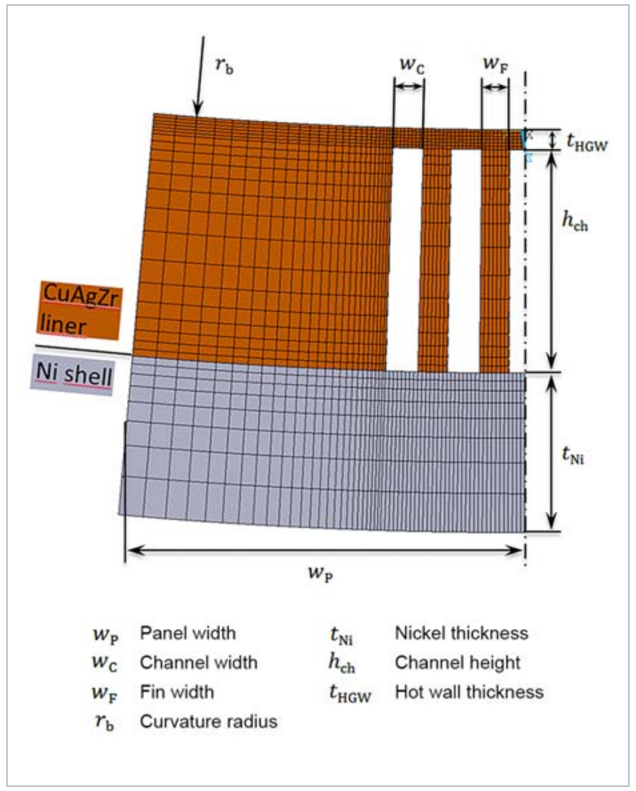

Fig. 6: Modified geometry parameters defining the panel design

The design generation is based on the Latin Hyper Cube sampling method. Thereby, each parameter is uniformly distributed over a band width of ± 20% in relation to the initial values of the original design. For the curvature radius, the initial value is correlated to the combustion chamber curvature.

At first, the underlying Finite Element (FE) simulation calculates the temperature field based on the lasers heating input and the convective nitrogen cooling through the cooling channels as schematically displayed in Fig. 2 (see page 31). The subsequent mechanical FE simulation considers the temperature field, internal channel pressure and symmetry conditions along the symmetric plane. With the constitutive material formulation of the copper alloy, the panel deformations are calculated and the stress, strain and damage fields are analyzed. Reference [2] can be consulted for a detailed description of the FE simulation and the post processing used for characterizing the damage behavior inside the laser loaded wall, especially in the hot wall of the mid cooling channel.

The temperature distribution inside the panel as well as the overall stiffness of the panel is influenced due to the variation of the displayed design parameters. Subsequently, the loading of the laser loaded walls changes and leads to the variations of the stress-strain-hysteresis, which is considered during the optimization process.

Optimization criteria

In order to formulate a minimization problem, an error value 'Err' is defined. 'Err' is quantifying the strain deviation of the current design from the goal behavior of the combustion chamber. As exemplarily depicted in Fig. 7 (see next page), for the hot wall center point position of the mid channel, the difference between the mechanical hoop strain after the first load cycle is measured for all three wall positions: top, center and bottom. The geometric mean value of the difference value then defines the error value that is to be minimized:

$$Err = \sqrt{\frac{1}{3}\sum_{bottom}^{top}(\Delta\varepsilon_{\theta\theta})^2} \quad with\ \Delta\varepsilon_{\theta\theta} = \varepsilon^{panel} - \varepsilon^{target}$$

The error value is calculated within the APDL script after the FE simulation for each single design and afterward transmitted back to optiSLang.

Sensitivities and best design

For the sensitivity analysis, 100 designs are created by varying the 7 design parameters. 98 designs are calculated successfully and allow the investigation of the model sensitivities according to the described error definition. The same simulation results are used for the generation of a Metamodel of Optimal Prognosis (MOP), which is applied for optimization purposes.

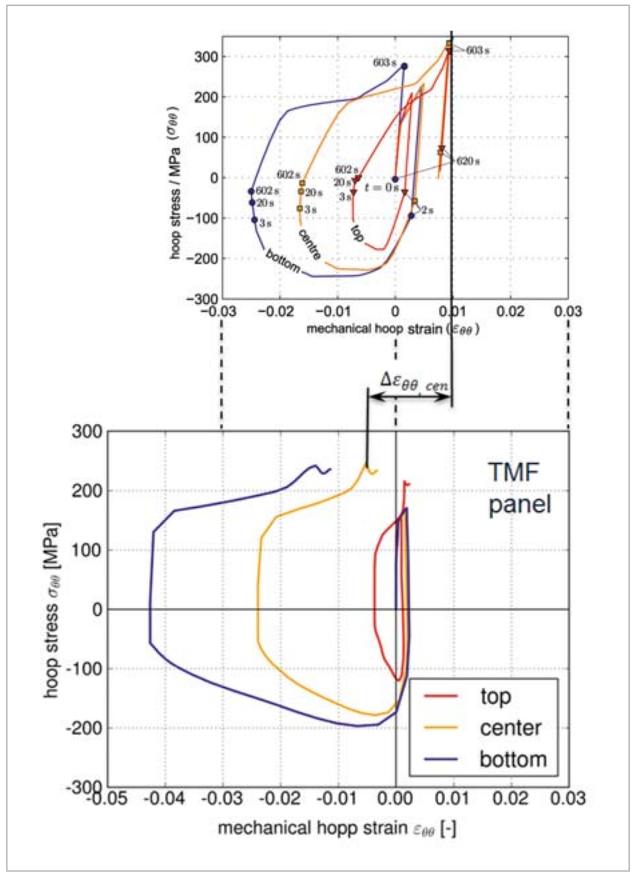

Fig. 7: Lateral mechanical strain deviation after the first load cycle between the goal level of the combustion chamber and the current level of the treated design, here, exemplarily for the center wall position

Parameter sensitivity

The results of the sensitivity analysis provided by optiSLang are presented in Fig. 8. It turns out that the curvature radius shows the highest influence and a large radius reduces the error value. Although this leads to the notion that maximizing the curvature radius towards a flat shape is beneficial for the damage behavior, it has to be mentioned that the error value minimizes in the upper level of the design space of parameter r_b. Hence, the curvature is needed to be considered for the optimization. Regarding the overall panel width as the second most influential parameter, a more intuitive result could be seen. Having less material in the bulky side volume, the overall cooling behavior is improved, which also stiffens the structure during the cooling phase. While the compressive deformation during the hot phase leads to compressive plastification in lateral direction, the post cooling moves the investigated wall into a tensile stress state increasing its influence by a colder and stiffer side structure. The strain level is then pulled towards the tensile domain in post cooling phase. Further, the residual strain turns out to be sensitive to the liner thickness $t_{liner}=h_{ch}+t_{HGW}$. Here, a thicker liner leads to a reduction of the error value.

It also can be seen that the error values are less sensitive towards the design parameters defining the actual channel structure and hot wall dimension. Therefore, hot wall thickness, channel width and distance can be modified with minor influence on the actual damage behavior. This fact is important regarding the application of the TMF panel test for future combustion chamber validation efforts.

Best design - geometry evolution

From the results of the sensitivity analysis, a Metamodel of Optimal Prognosis (MOP) was created. The actual optimization task was performed on the basis of the MOP, which showed a Coefficient of Prognosis (CoP) = 96%. The result of the optimization incorporates the findings of the sensitivity analysis of a reduced panel width, larger liner thickness and the optimal bending radius as depicted in the geometry drawings in Fig. 9 with the initial geometry on the left and the optimized geometry on the right.

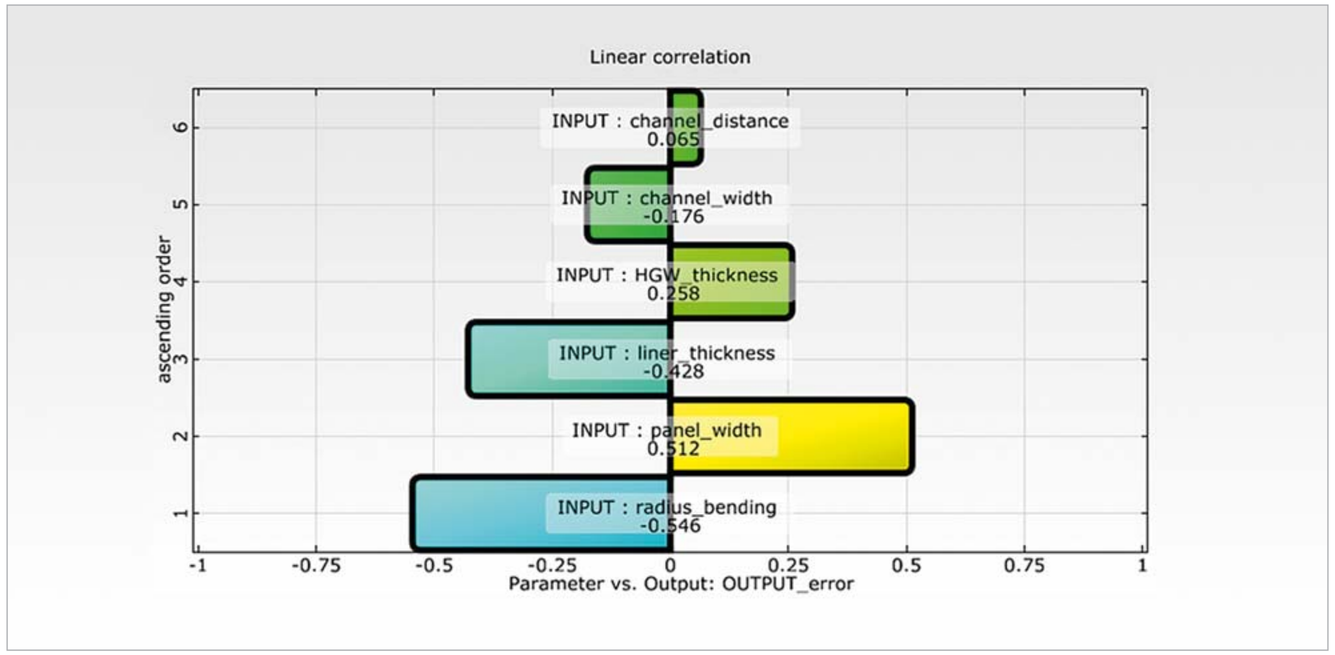

Fig. 8: Sensitivities towards design parameters

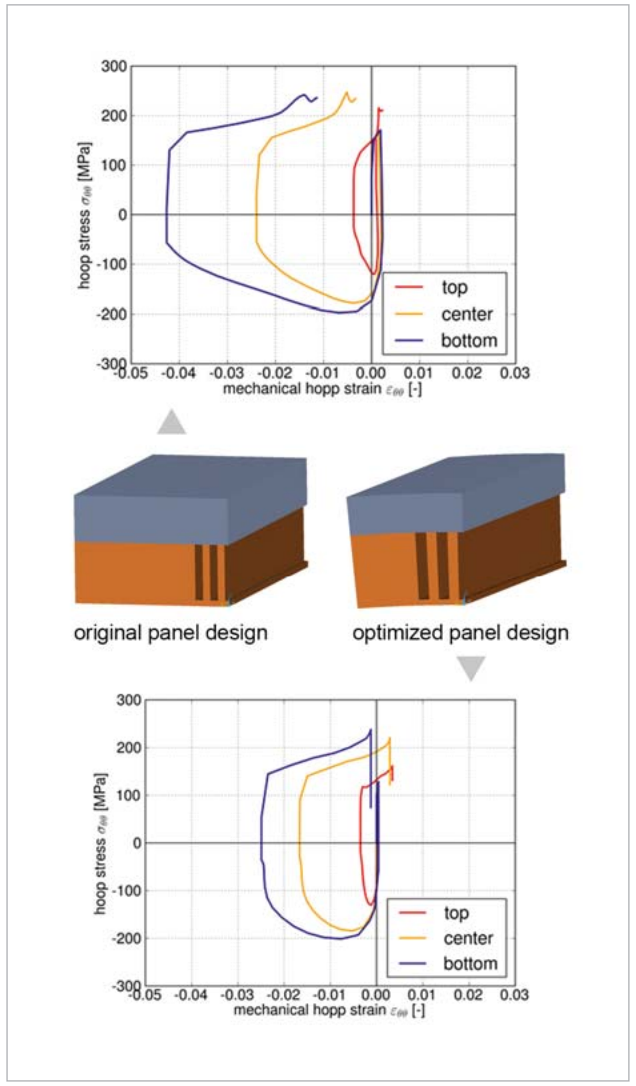

Fig. 9: Original panel design (top) compared to the optimized panel design (bottom)

While observing the stress strain hysteresis of the first cycle of both designs in Fig. 9, it can be seen that the optimized design clearly tends to the tensile strain domain during the cooling phase. Hence, it is shown that modifications of the panel design can be used to change the stress and strain behavior of the hot wall towards the desired direction. Due to the mentioned modifications, the residual strain accumulated in the tensile domain as well as it was observed in the combustion chamber. The optimized panel design increased the representativeness on the hot gas wall damage behavior.

Conclusion

In the present study, the potential enhancement of the currently used TMF panel design was investigated in order to find a panel shape that shows a damage behavior similar to the combustion chamber. Therefore, an automated TMF panel test simulation was created including the generation of a FE model and running the thermal and mechanical analysis based on prior defined design parameters. In addition, the results of the automatically performed comparison between the behavior of the current design and the one of the combustion chamber were reprocessed back as output variables. With the help of the analyzing capabilities of optiSLang, the sensitivities of the parameter variations regarding the panel's damage behavior could be recognized and verified. It was shown that a curvature of the panel has a high influence on the hot wall behavior as well as on the thickness and width of the panel. On the other hand, the hot wall thickness, channel width and the fin width had a lower influence, which allowed their modification without violating the representativeness of the panel to the combustion chamber. This result is especially important regarding a future application of the TMF panel tests towards combustion chamber qualification. With the results of the sensitivity analysis, a MOP based optimization procedure was launched resulting in a best design capable of fulfilling the objectives of this investigation. Hence, it was found that the right parameter adjustments on the panel design lead to a combustion chamber like damage behavior. This allowed a TMF panel testing of the combustion chamber representatives.

Author //

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