Design and Test of an Ultrasonically Absorptive Thermal Protection Material for Passive Hypersonic Transition Control

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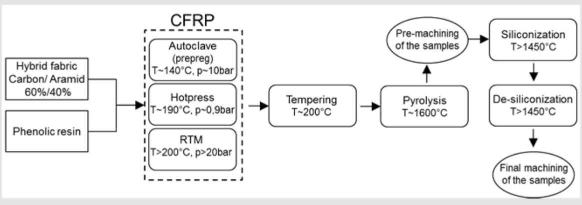
Motivation

In hypersonic boundary layers, with second-mode instabilities being the dominant mechanism leading to boundary layer transition, ultrasonically absorptive coatings offer the potential to control the instability growth and thus delay transition. However, to achieve practical relevance with respect to the hypersonic flight regime the ultrasonically absorptive materials need to withstand very high shear stresses and heat loads typical for such flight conditions. In the past two years DLR developed and optimized a new porous C/C-SiC material to fulfill this need.[1,2] The present study concludes our experimental and numerical efforts. It describes the design strategy including the stability analysis of the flow field at the point of operation, the material design, the acoustic characterization of the C/C-SiC material and the final tests in the High Enthalpy Shock Tunnel Göttingen (HEG).[3]

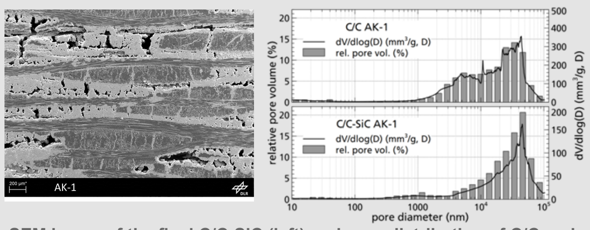
C/C-SiC – Manufacturing & Properties

Three different industrial processes to manufacture ceramic matrix composite (CMC) materials were investigated in the scope of the project. All green bodies were made of commercially available 2D hybrid fabrics using a mix of carbon and aramid fibers. The composition was chosen to be 38.80% aramid fibers and 61.20% carbon fibers. Additionally, different resin systems were compared to standard phenolic resin. The process leads to CMC materials stable up to 1800 K. An overview on the manufacturing process is provided below.



Scheme of the CMC manufacturing process.

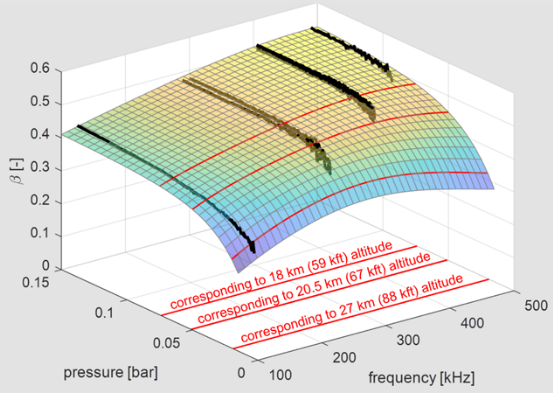
The obtained C/C-SiC samples were analyzed and rated with respect to mechanical strength, surface homogeneity, flow through resistance, porosity and pore size distribution. The latter property is shown below together with a scanning electron microscopy image (SEM) of the surface, for the CMC material chosen for the validation tests in the DLR High Enthalpy Shock Tunnel Göttingen.



SEM image of the final C/C-SiC (left) and pore distribution of C/C and C/C-SiC (right).

Ultrasonic Absorption Properties

Direct absorption measurements in a frequency range of 125 kHz to 490 kHz were conducted on CMC samples using an acoustic test bench. The test bench was further refined to allow testing at background pressures relevant to hypersonic flight. The tests on the C/C-SiC material chosen for wind tunnel testing revealed significantly improved absorber properties, compared to C/C used in the past to delay hypersonic boundary layer transition, which will increase the damping of 2nd mode instabilities and thus lead to a larger transition delay.

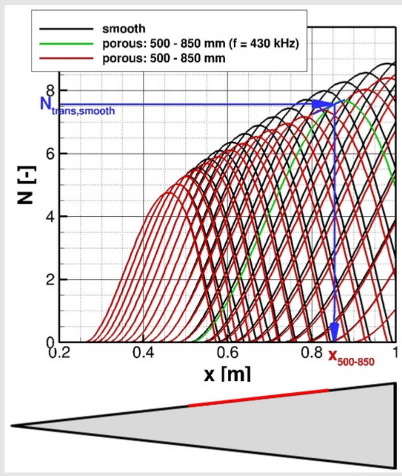


Absorption coefficient of the final C/C-SiC as function of pressure and frequency. The Homogeneous Absorber Theorie was fitted to the experimental results to provide a boundary condition for the LST.

Furthermore, the refinement of the setup allowed to differentiate between the uncertainties caused by the measurement chain and the heterogeneity of the porous surface properties due its random nature. The above provided absorption coefficient distribution as function of frequency and background pressure served as boundary condition for the linear stability analysis.

Linear Stability Analysis

Linear stability analysis (LST) was used in combination with a porous surface boundary condition based on the adapted Homogeneous Absorber Theory to support the design process of the final wind tunnel model for tests in HEG. The impact of different porous insert lengths on the transition location were investigated.

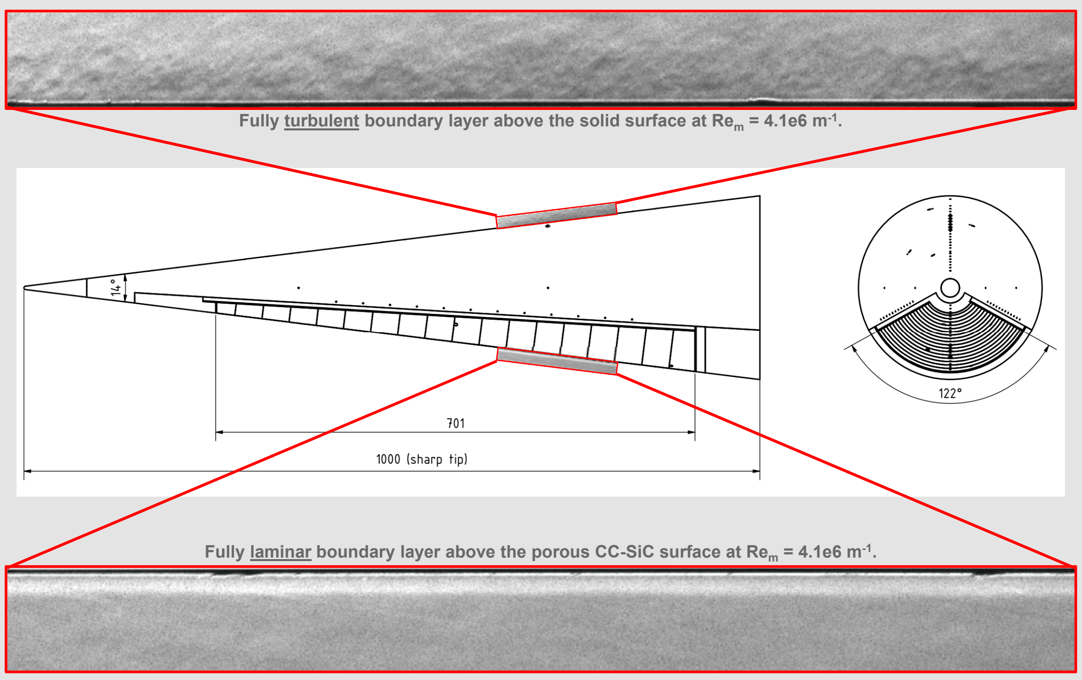


N-Factor distribution above the cone surface for a smooth and porous surface, the latter with a given extent.

References

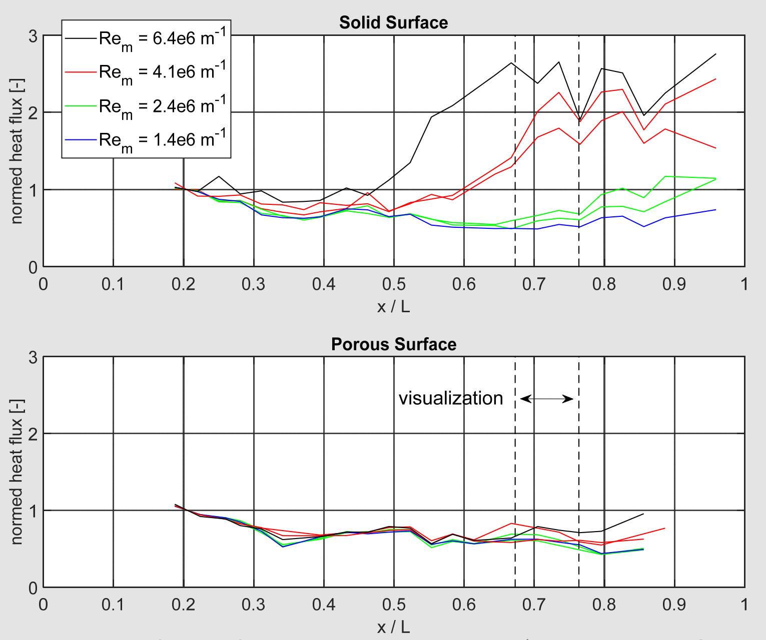
[1] Dittert et al., Process Optimization of Ceramic Matrix Composites for Ultrasonically Absorptive TPS Material, 2018, AIAA 2018-2947
[2] Wagner et al., Experimental and numerical acoustic characterization of ultrasonically absorptive porous materials, 2018, AIAA 2018-2948
[3] The High Enthalpy Shock Tunnel Göttingen of the German Aerospace Center (DLR), Journal of Large-Scale Research Facilities, 2018, DOI: 10.17815/jlsrf-4-168

Experimental Results in HEG Confirming Strong Boundary Layer Stabilization



Fully turbulent boundary layer above the solid surface at $Re_m = 4.1e6\ m^{-1}$.

Fully laminar boundary layer above the porous CC-SiC surface at $Re_m = 4.1e6\ m^{-1}$.



Normalized surface heat flux along the cone. $Re_m = 4.1e6\ m^{-1}$ corresponds to the Schlieren visualization shown on the left.

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