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Results of a Liquid Rocket Booster (LRB) Nozzle Throat Related Thermo-Mechanical Fatigue (TMF) Panel Test

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Results of a TMF test based on a (liquid rocket booster hot-run related) laser-on hold time of 200 s are shown in this manuscript. A (supercritical N_2) coolant inlet temperature of 160 K and a coolant outlet pressure of 5 MPa were applied during the cold flow. Due to fixed control valve settings and LN_2 pump speed during the (laser-on) hot rut, these two values increased slightly during each thermal loading period of the TMF test. The coolant mass flow rate was tuned to obtain an average heat flux of 20 MW/m^2 into the TMF panel structure in the center of the laser-loading area. By a fine-tuning of the laser power, a maximum TMF panel wall temperature of 1000 K was achieved from the 2nd cycle to the failure cycle. The most important result of the TMF test is the observed fatigue life of 369 cycles to failure. A series of additional measurements provide e.g. the 2d thermal field and the 2d displacement field during each hot run.

Key Words: LRB, LRE, LCF, CuCrZr, TMF

Nomenclature

$\dot{q}$	:	heat flux density, MW/m^2
T	:	temperature, K
t	:	time, s
p	:	pressure, MPa
l	:	length, mm
φ	:	angle, °

Subscripts

In	:	inlet
out	:	outlet
max	:	maximum

1. Introduction

The strong demand for light-weight structures, which is typical for space transportation systems, leads to a close-to-the-limit design of all involved components – including the rocket engines. The combined thermally and mechanically induced (ratchetting caused) tensile rupture, Low Cycle Fatigue (LCF) and creep failure of hot gas walls is one of the strongest limiting factors of the number of re-uses of key rocket engine components like combustion chambers and nozzles.

The development and flight qualification of such components includes on top of many other actions structural and fatigue life analyses of the key components and full scale tests of the whole rocket engine. Thermo-Mechanical Fatigue (TMF) panel tests can provide essential validation data for these numerical analyses and reduce the need for full scale tests considerably. Therefore, TMF panel tests have the potential of both, avoiding failure due to non-validated numerical design analyses as well as saving full scale testing cost.

During a TMF panel test, only a small section of the hot gas wall of the real engine (the so called TMF panel) is tested. For this TMF panel, a realistic (active) cooling similar to the full scale rocket engine is applied. For TMF test safety reasons, the original coolant (nowadays in most cases Kerosene or supercritical H_2) is replaced by supercritical N_2. The N_2 mass flow rate is adjusted to result in a similar maximum TMF panel temperature, related to the maximum hot-gas side wall temperature of the liquid rocket engine combustion chamber or nozzle.

The key component of a TMF panel test bench is a heating device for the thermally loaded side of the tested wall component. For the TMF panel test bench at DLR Lampoldshausen, a diode Laser with a wave length of 940 nm was chosen. This Laser was especially designed by the diode laser producer DILAS in order to obtain a maximum optical output of 11 kW. This results in an energy density of up to 20 MW/m^2 at the focal plane (“top hat” profile with a rectangular 10 mm x 34 mm plateau). Whereas for previous tests with DLR TMF panels always a (booster-parallel core stage liquid rocket engine hot-run duration related) laser-on hold time of 600 s was applied for all loading cycles (up to failure), the results of the AKIRA[1)] TMF test shown in this manuscript are based on a (liquid rocket booster hot-run related) laser-on hold time of 200 s. A comparison between TMF panel test conditions and comparison to liquid rocket booster hot-run conditions (@ the nozzle throat) is shown in Table 1.

2. Components of the TMF panel test bench at DLR Lampoldshausen

2.1. The heating device of the TMF panel test bench

The key component of a TMF test bench is a heating device for the tested wall component. For medium heat flux applications, the following heating devices have been used:

- quartz tube radiant heaters without elliptical mirrors for flat nuclear rocket nozzle tube TMF panels,[2)]
- quartz tube radiant heaters with elliptical mirrors for rotatory symmetric jet engine test specimens.[3,4)]

Table 1. TMF panel test conditions and comparison to liquid rocket booster hot-run conditions (@ the nozzle throat).

thermal and mechanical loading	TMF panel test	nozzle throat of a typical LRB
maximum heat flux, caused by the thermal loading	20 MW/m^2	about 100 MW/m^2
maximum temperature, caused by the thermal loading	1000 K	about 1000 K
applied coolant and its inlet temperature	160 K (supercritical N_2)	about 30 K (supercritical H_2) to ambient (liquid Kerosene)
pressure difference between the coolant and the thermally loaded side	about 5 MPa	about 10 MPa

However, combustion chambers of liquid propellant rocket engines are exposed to much higher heat flux densities compared to nozzle extension and jet engine structures. Consequently, realizing relevant environmental conditions inside a TMF test bench requires much higher power densities. Even a local combustion process under ambient pressure does not provide the high energy density which is necessary for this purpose.

Therefore, an optical heating device with a high energy density is required. The heating device of the TMF panel test facility at DLR Lampoldshausen was designed and built by DILAS Diodenlaser GmbH.[5,6)] The key technical parameters of this diode laser are given in Table 2.

Table 2. Key technical parameters of the diode laser of the TMF test bench at DLR Lampoldshausen.

Parameter	**Value**
Wavelength	940 nm
Maximum optical output power	11 kW
Distance from the optics module to the focal plane	415 mm
Plateau cross section of the beam at the focal plane for the 8 MW/m^2 laser optics	19 mm x 51 mm
Plateau cross section of the beam at the focal plane for the 25 MW/m^2 laser optics	10 mm x 32 mm
Homogeneity	better than ±5%
Operational mode	cw

In order to vizualize the intensity distribution of the laser beam at its focal plane, the infra-red laser light was transformed into visible light by fluorescent sheets as shown in Figure 1.

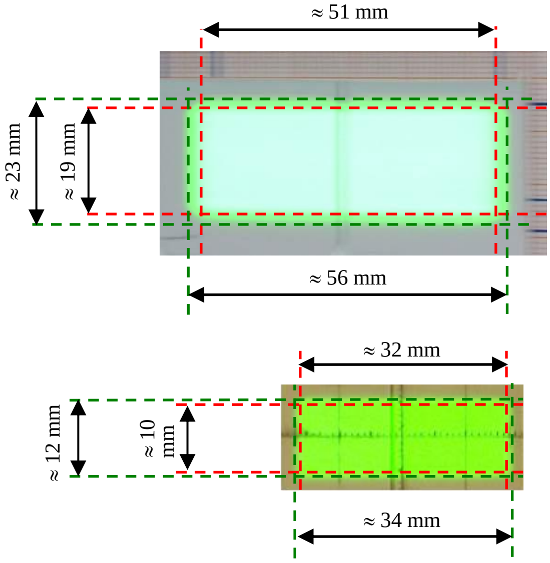

Figure 1: Visualization of the intensity distribution of the laser beam at the focal plane with an infra-red conversion screen for the 8 MW/m^2 optics (left) and for the newly acquired 28 MW/m^2 optics (right).

With the 19 mm x 51 mm laser optics, a typical heat flux of 8 MW/m^2 can be obtained in the plateau cross section of the laser beam as shown on the top of Figure 1. This optics is well suited for testing nozzle extension wall structures. Results of such tests were reported in references 7) and 8). With the newly acquired 10 mm x 32 mm laser optics, a laser power density of up to 25 MW/m^2 can be obtained in the plateau cross section of the laser beam as shown on the bottom of Figure 1. This is closer to the conditions equivalent to the heat flux in the nozzle throat cross section of a Liquid Rocket Booster engine than the 8 MW/m^2 of the 19 mm x 51 mm laser optics.

2.2. The TMF panel housing

In order to reduce water vapor condensation effects on the laser loaded side of the TMF panel wall material during the pre- and post-cooling phases of the TMF panel test, a TMF panel housing as shown in Figure 2 was designed.

Figure 2: TMF panel test bench with laser head (left), infra-red camera (top) and TMF panel housing (side walls removed, right).

2.3. The measurement devices of the TMF panel test bench at DLR Lampoldshausen

2.3.1 The laser power meter

For the determination of the local heat flux into the TMF panel (which provides the heat flux distribution boundary condition for a thermal validation analysis of the TMF panel, the following values have to be measured:

- the absorption of the laser loaded surface at the laser wave length,
- the laser power distribution in the focal plane of the laser beam, and
- the total optical output power of the laser.

A special version of the PRIMES Power Monitor with an aperture of 250 mm x 50 mm as shown on the left-hand side of Figure 3 was used for the measurement of the laser power.

Figure 3: Devices for characterizing the laser beam: laser power meter (left) and laser beam profiler (right).

For laser power values between 1 kW and 12 kW, the measurement uncertainty of the system is better than ±2% of the measured value.[9)]

2.3.2 The laser beam profiler

The distribution of the laser power in the focal plane of the laser beam was determined by the PRIMES laser beam monitor BM100 (as shown on the right-hand side of Figure 3) with a resolution of 256 x 128 pixels and a measurement uncertainty of smaller than ±3% of the measured value.

2.3.3 The laser wave length pyrometer

The absorption of the laser loaded surface at elevated temperatures will be measured by a pyrometer with an identical wavelength as the laser wavelength. This high end transfer standard pyrometer IMPAC IS12-TSP is shown on the left-hand side of Figure 4.

Temperatures can be measured with this pyrometer with an uncertainty of ± 0.15% of the measured value ± 1 °C at a measurement range between 430 °C and 1300 °C. In addition, a narrow band pass filter with a center wavelength of 940 nm ± 4 nm and a half width of 20 nm ± 4 nm was used.

2.3.4 The infra-red camera

During the TMF test, the 2d thermal field at the laser loaded side of the TMF panel was measured by an infra-red camera (as shown on the right-hand side of Figure 4) with a resolution of 640 x 512 pixel, a maximum acquisition rate of 100 Hz and a measurement range of 300 °C to 1500 °C.

Figure 4: Devices for the determination of the emissivity of the TMF panel coating during pre-tests: laser wavelength pyrometer (left) and infra-red camera (right).

Related to a black body, the measurement uncertainty of this infra-red camera is lower than ± 1% of the measured temperature value. To avoid a possible influence of reflected infra-red laser radiation to the temperature measurement, a narrow band pass filter with a wavelength of 3.99 µm was used.

2.3.5 The deformation measurement systems

During the TMF test, the deformation of the TMF panel was measured by an image correlation[10)] system as shown on the left-hand side of Figure 5. In order to obtain the lowest possible measurement uncertainty, a system consisting of two 16 megapixel cameras was selected. This measurement system requires the application of small speckle marks to the surface of the TMF panel and allows for the measurement of 3 component (u_x, u_y, u_z) 2d displacement fields on the surface of the TMF panel before, during and after the laser loading. After the completion of the TMF test, the surface geometry and the cross section of the TMF panel was assessed by a digital microscope as shown on the right-hand side of Figure 5. The out-of-plane component of the surface geometry was determined by the "depth from defocus" technology with a 500 nm resolution step motor.

Figure 5: Devices for the measurement of the deformation of the TMF panel during the TMF test: stereo camera system (left) and after the TMF test: digital microscope (right).

3. Pre-test characterization of the TMF laser beam in its focal plane

The laser beam profiler as shown on the right-hand side of Figure 3 was used for the characterization of the beam of the TMF laser in its focal plane. The measurement shown in Figure 6 is related to the cross section of the laser beam in 5° tilted direction (as applied to the surface of the TMF panel).

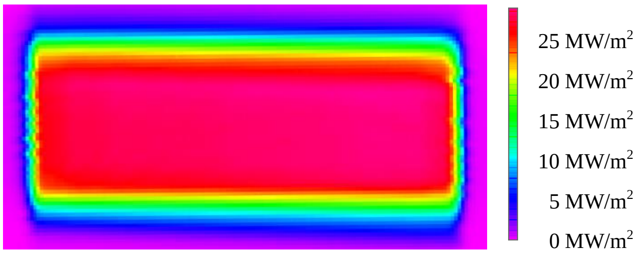

Figure 6: Profile of the TMF laser in its focal plane for an optical output laser power of 11 kW.

4. The Liquid Rocket Booster (LRB) nozzle throat TMF panel hardware

Cooling channel dimensions almost completely identical to the ones described in 11) were assumed for the liquid booster nozzle throat TMF panel. These geometric parameters are summarized in Table 3.

Table 3. Cooling channel parameters of the liquid booster nozzle throat TMF panel.

Parameter	Value
Width of the cooling channels	1.3 mm
Height of the cooling channels	9.0 mm
Angle between adjacent cooling channels	1.0 °
Total number of cooling channels in the TMF panel	7
Thickness of the laser loaded wall	1.0 mm
Curvature radius of the (cylindrical) laser loaded surface	130.0 mm

In contrary to all other TMF panels tested at DLR Lampoldshausen (containing planar laser loading surfaces), the laser loaded surface of the liquid booster nozzle throat TMF panel has a cylindrical surface in order to obtain an accumulation of tensile deformation in the centerline cooling channel of the liquid booster nozzle throat TMF panel. Photographs of the TMF panel prior to the TMF test without and with coating are shown in Figure 7.

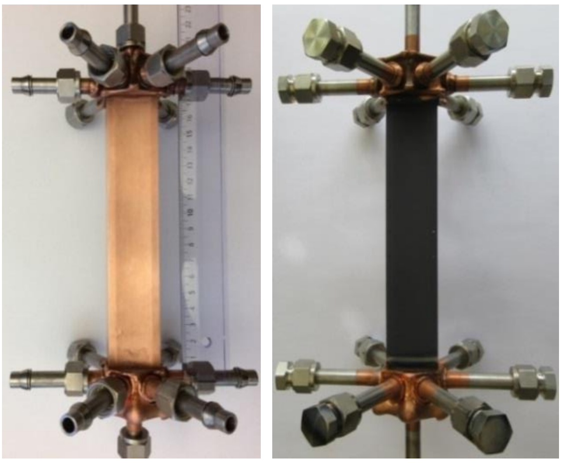

Figure 7: The liquid booster nozzle throat TMF panel made from CuCrZr in the laser-loading section (left) and coated TMF panel (right).

The absorption and emissivity increasing coating on the laser-loaded side of the TMF-panel as shown on the right-hand side of Figure 7 ensures:

- Avoiding as much as possible reflected laser light which would damage TMF measurement devices such as the ones shown at the right-hand side of Figure 4 and on the left-hand side of Figure 5. Without the TMF panel coating, the pure CuCrZr surface of the TMF panel (shown on the left-hand side of Figure 7) would act almost like a mirror at the spectral range of the laser (940 nm).
- Increasing the accuracy of the optical temperature measurement. Without the TMF panel coating, the low emissivity of the pure CuCrZr surface would increase strongly during the TMF test due to an oxidation of its laser-loaded surface as well as due to a straining-caused roughness increase of the laser loaded surface.
- Application of high-contrast speckle marks on the surface of the TMF panel in order to measure the surface deformation by a successive application of the stereo camera system shown on the left-hand side of Figure 5 and some image correlation software.

5. Liquid Rocket Booster (LRB) nozzle throat TMF panel test conditions

The boundary conditions, applied to the Liquid Rocket Booster nozzle throat TMF panel shown in Figure 7 are summarized in Table 4.

Table 4. Cooling channel parameters of the liquid booster nozzle throat TMF panel.

Parameter	Value
Heat flux density into the TMF panel (averaged over top hat intensity area)	25 MW/m^2
Maximum TMF panel temperature during the (laser on) hot run	1000 K
Inlet temperature of the coolant GN_2 (controlled)	160 K
Outlet pressure of the coolant GN_2 during the (laser off) cold flow (controlled)	5 MPa
Outlet pressure of the coolant GN_2 during the (laser on) hot run (not controlled)	5.5 MPa

6. Liquid Rocket Booster (LRB) nozzle throat TMF panel test results

6.1. Number of cycles to failure

The most important result of a TMF test is the number of cycles to failure. Although the maximum TMF panel temperature T_{max} was carefully controlled to 1000 K, the fatigue life of the TMF panel is relatively high: 369 cycles.
The reason for this unexpectedly large fatigue life is the relatively low cyclic strain of less than 1% in each (laser on / laser off) loading cycle.[12)] However - in the inner liner of the nozzle throat of a high-pressure Liquid Rocket Booster, the

cyclic strain is about 2%.

6.2. 2d temperature distribution of the laser-loaded area of the Liquid Rocket Booster nozzle throat TMF panel

The 2d temperature distribution of the Liquid Rocket Booster nozzle throat TMF panel at the end of the 1st, 100th, 200th, 300th, 350th and 369th laser-on-loading cycles is shown in Figure 8.

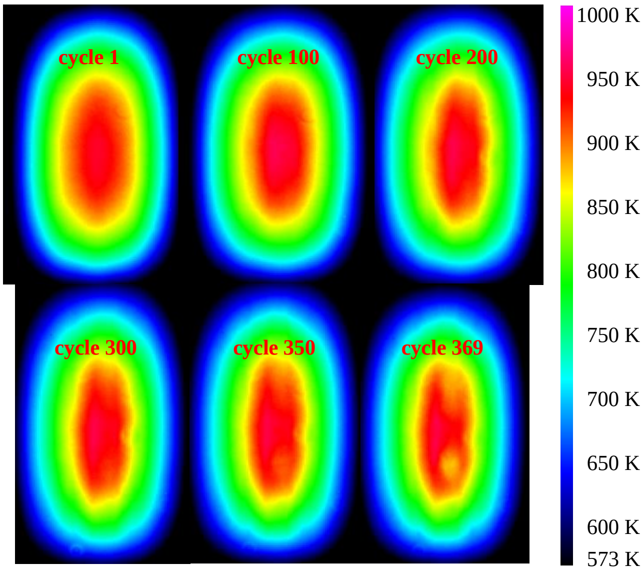

Figure 8: Thermal fields at the laser loaded area of the TMF panel at the end of the laser loading cycles as recorded with the infra-red camera shown on the right-hand side of Figure 4.

6.3. Temperature line plots in the laser-loaded area of the Liquid Rocket Booster nozzle throat TMF panel

In Figure 9 and Figure 10, temperature line plots in axial direction and in lateral direction of the TMF panel are plotted.

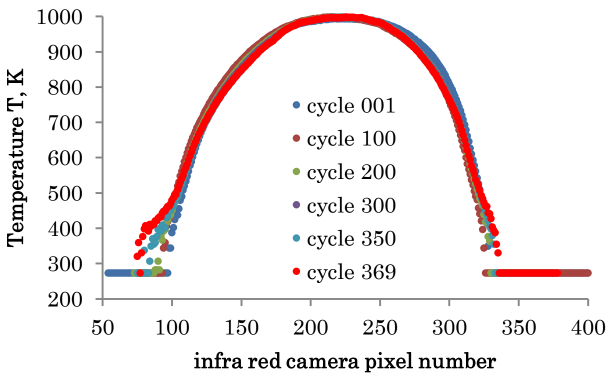

Figure 9: Temperature line plot in axial direction of the TMF panel as recorded with the infra red camera shown on the right-hand side of Figure 4.

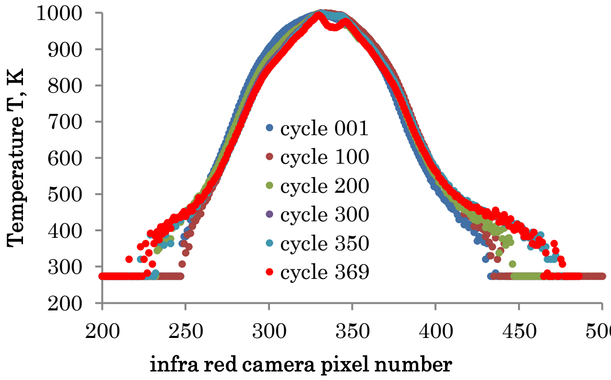

Figure 10: Temperature line plot in lateral direction of the TMF panel as recorded with the infra red camera shown on the right-hand side of Figure 4.

6.4. Deformation of the cross section area of the Liquid Rocket Booster nozzle throat TMF panel

The deformation of the failure cross section of the Liquid Rocket Booster nozzle throat TMF panel is shown on the right-hand side of Figure 11. For comparison with the initial cross section geometry, a digital microscope picture of a cross section far away from the failure cross section is shown on the left-hand side of Figure 11.

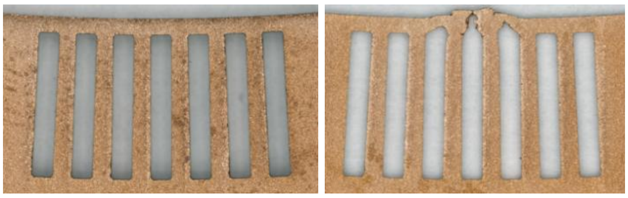

Figure 11: Cross section areas of the Liquid Rocket Booster nozzle throat TMF panel before testing (left) and after LCF failure (right) as recorded with the digital microscope shown on the right-hand side of Figure 5.

6.5. Evolution of the out-of-plane deformation in the laser-loaded area of the Liquid Rocket Booster nozzle throat TMF panel

In Figure 12, the evolution of the surface relief of the middle cross section of the laser-loaded area of the Liquid Rocket Booster nozzle throat TMF panel is shown.

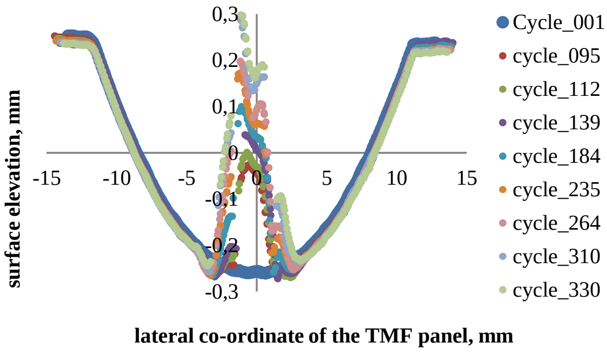

Figure 12: Surface relief of the Liquid Rocket Booster nozzle throat TMF panel as recorded with the deformation measurement system shown on the left-hand side of Figure 5.

In Figure 13, the evolution of the maximum out-of-plane deformation in the laser-loaded area of the Liquid Rocket Booster nozzle throat TMF panel is shown.

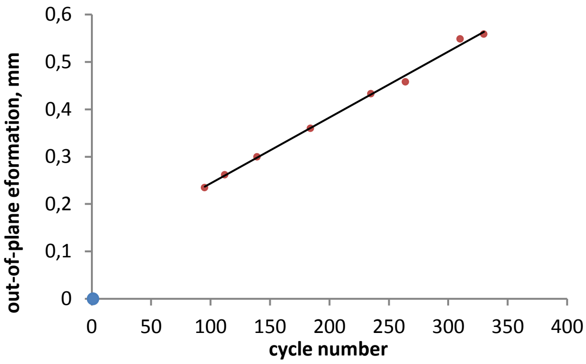

Figure 13: maximum out-of-plane deformation of the Liquid Rocket Booster nozzle throat TMF panel as recorded with the deformation measurement system shown on the left-hand side of Figure 5.

7. Conclusion

Experimental results of a Liquid Rocket Booster nozzle throat TMF panel test have been shown. At a later point in time, these test results can e.g. be used for:

- The comparison of the fatigue life of different materials under identical loading conditions,
- the validation of structural FE analysis methods,
- the validation of numerical fatigue life analysis methods.

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