Hot fire testing of a subscale combustion chamber demonstrator made with selective laser melting

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Abstract

The design of cooling channels has significant influence on the life time of highly thermally loaded combustion chamber structures. Today, channels are typically milled and closed with electrical deposition, or alternatively welded or brazed from tubes. Additive laser manufacturing (ALM) enables the creation of 3D structures that cannot be manufactured with conventional production methods, for example more complex geometries of optimized cooling channels in the combustion chamber walls of rocket engines. In the frame of the DLR-study LAMP (Laser Additive Manufacturing for Propulsion) at the DLR Institute of Space Propulsion, the applicability of ALM for production of rocket propulsion components was investigated.

1. Introduction

The design of cooling channels has significant influence on the life time of highly thermally loaded combustion chamber structures. The history of the cooling system design is strongly interconnected with technological evolution.

Today, channels are typically milled and closed with electrical deposition [1], or alternatively welded or brazed from tubes. Volvo Aero Corporation developed and successfully applied new technology based on the laser welded channel wall technology for the production a cooled wall structure, the so called “Sandwich Nozzle” [2], [3].

The additive manufacturing methods (AM) are a relative new technique which shows a rapid evolution in recent years. To these methods belong such manufacturing processes as Vacuum Plasma Spraying (VPS), Laser Metal deposition (LMD), Selective Electron Beam Melting and Powder-bed Selective Laser Melting (SLM) [4], [5]. The last process uses a powder bed in which the components are manufactured layer by layer by fusion of melted powder. SLM is of major interest for cooled structures because this method allows the production of the cooling channel with relatively good surface finish and with a wide spectrum of design solutions. Additive manufacturing enables the creation of 3D structures that cannot be manufactured with conventional production methods, for example more complex geometries of optimized cooling channels in the combustion chamber walls of rocket engines.

In the frame of the DLR-study LAMP (Laser Additive Manufacturing for Propulsion) at the DLR Institute of Space Propulsion, the applicability of SLM for production of components for rocket propulsion was investigated. The focus of the study was the development of basic technologies and design methods as well as the verification of design solutions for key components of an SLM combustion chamber. The activities included the investigation of the most important design aspects of combustion chambers, such as gas tightness, geometric accuracy, and surface roughness. The results of preparatory work was used for the design of a combustion chamber from a heat-resistant nickel alloy. Construction of the integral combustion chamber shows the advantage of the SLM process; the combustion chamber with cooling passages and throat were produced as an integral part in one manufacturing process. The design of the cooling channels, which helically encompass the cylindrical combustion chamber, facilitate optimal cooling effect. The functionality of the SLM combustion chamber has been demonstrated in hot firing testing, preliminary results of which are presented in this paper.

2. Preparatory work

Because of the limited available building volume in the poweder bed of the SLM machine used, a low thrust chamber (500 N) configuration has been chosed as a demosntrator. As the structural material, the well-established inconel 718 was chosen.

A major goal of the presented study was to understand the influence of the new manufacturing method on the design of the thrust chamber. Therefore, typical material parameters like the density and yield strength have not been especially investigated. For design and dimensioning, standard material properties from literature were used [4].

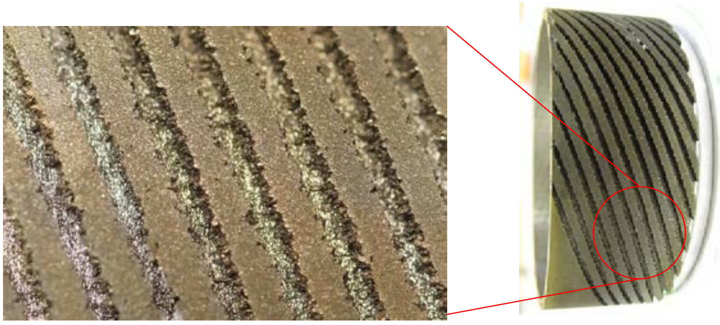


Figure 1: manufacturing test for the helical cooling channels

One of the most important parameters is surface finish, which has significant influence on heat transport processes and pressure drop in cooling channels. To define the influence of different cooling channel designs on the resulting inner surface texture, several preparatory test samples were produced (Figure 1). The surface conditions at different declination angle of the cooling channel wall were investigated. A rectangular channel with a generic dimension 1x1 mm with different angles of slope has been manufactured. The test samples simulated the helical cooling channel which will be described in more detail in the following chapter.

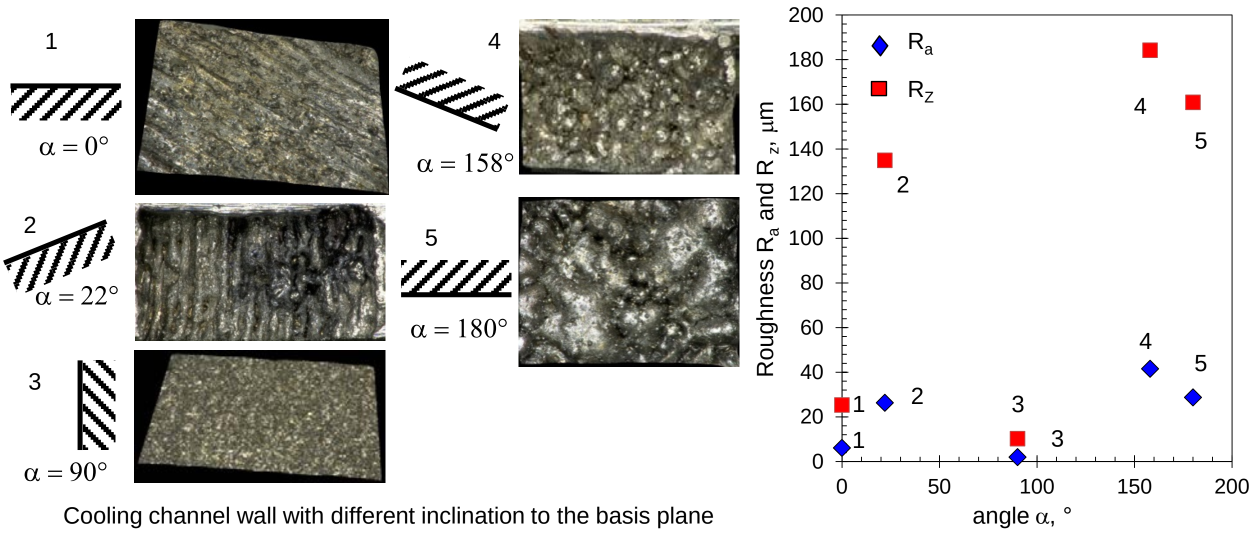


Figure 2: roughness of the SLM manufactured channel as a function from an angle of slope

An analysis of the 3D surface profile of the cooling channels was performed with an optical digital microscope with an enlargement of 1:200 that allowed high accuracy measurements (Figure 2). The images show that the most influence on the surface texture was not the powder grains, but soldered droplets of the laser-melted powder. The surface contains a pattern of the drop-shaped bumps. As a reference parameter, the arithmetic average of absolute of the roughness Ra and the average distance between the highest peak and lowest valley in each sampling length R_z were taken. It can be clearly seen that there is a high dependency of the roughness on the declination angle (α). While at α= 0° and 90° the surface is relatively smooth (R_a = 2-7 µm and R_Z = 10-25 µm), at α= 22°, 158° and 180°

the roughness is significantly higher. Here, Ra and R_Z reach values between 25-30 µm and between 150- 300 µm, respectively. The sample with α= 22° shows the strong anisotropy of the surface roughness associated with layered manufacturing.

Another important parameter is the porosity of the wall. The SLM manufactured combustion chamber structure has been tested with water at pressures up to 23 MPa and with Helium at a pressure of 1 MPa. The tests showed minimal leakage rates in both tests. The wall “transpires” at same locations (Figure 3). The Helium leakage is ca. 0.016 g/s at 1 MPa pressure in cooling channels more or less uniformly distributed over the cooled surface.

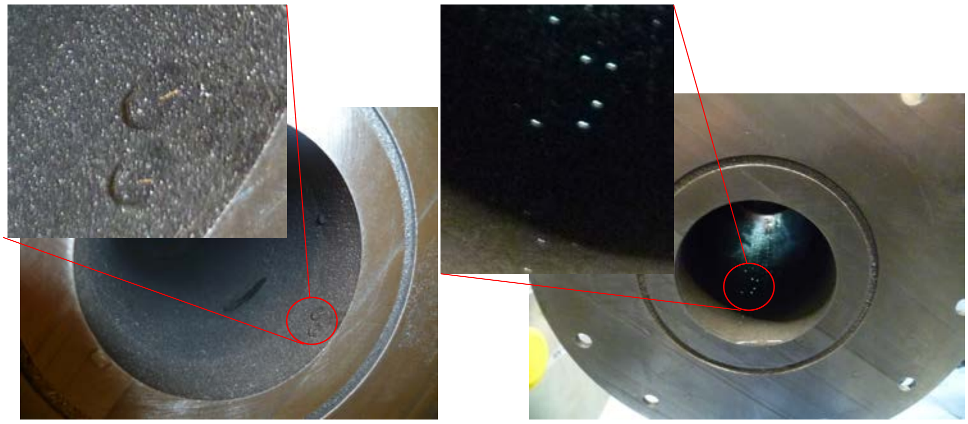
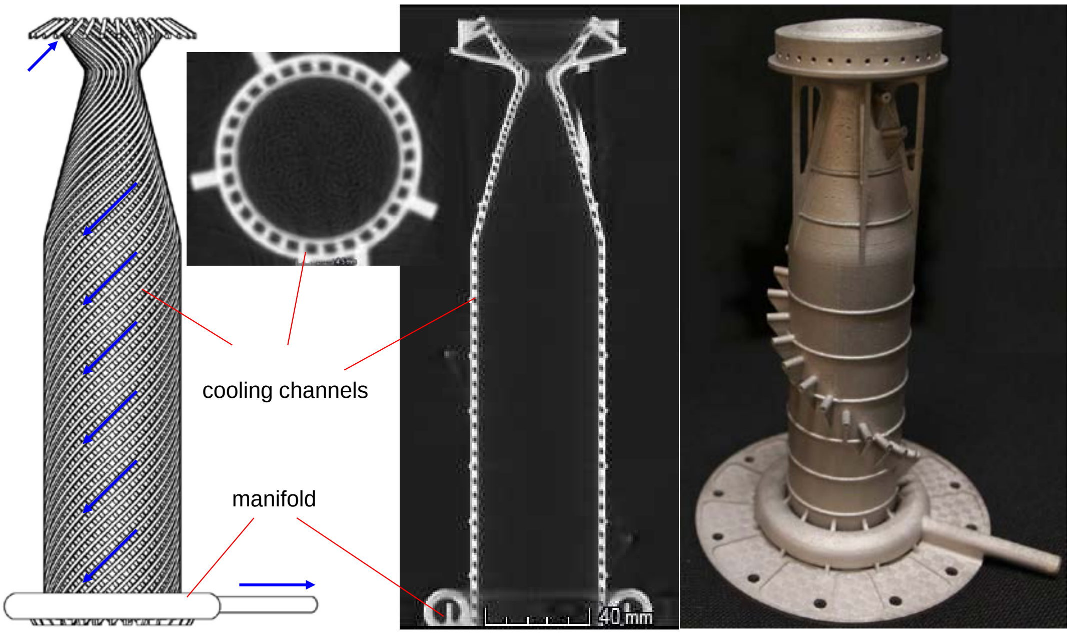


Figure 3: porosity test with water at 230 bar (left) and with Helium at 10 bar (right)

Additionally this test programme demonstrated good feasibility of the post-ALM processing methods, with milling and welding. The manufacturing precision of the produced test parts has been limited by the relative high roughness.

2. DLR subscale combustion chamber model “K”

The construction of the combustion chamber was realised with the target of an economic, robust design with low weight. Since in SLM manufacturing not the complexity, but the volume is the most important cost factor.



a) b) c)

Figure 4: ALM manufactured DLR subscale combustion chamber model „K“ a) structure of the cooling channels with coolant flow direction; b) 3D images from computer tomography; c) photo

The chamber inner diameter is 50 mm with a nozzle contraction ratio of 7.63. With a total length of 242 mm the chamber weighs only 1.6 kg. This light design was achieved by the following optimization measures.

By means of several barrel rings around the extent, the wall thickness of the chamber could be minimized. To retain thin chamber walls in the region of the nozzle throat, axial ribs were implemented. Analogous ribs were used to build the outflow collector as thin as possible.

For the cooling system design have been favoured the helical channels. This type of the cooling channels has been used by VULCAIN 2 and HM7 nozzle extensions, which are produced by welding helically curved rectangular tubes. It allows an optimal cooling efficiency to be reached with a minimal wall thickness and constant spacing between neighbouring channels. This design also provides good structural stability by minimising weight of the common construction. The 30 rectangular cooling channels have a width of 1.2 mm and a height of 1 mm. The material thickness between the bottom of the cooling channels and hot gas surface is 0.7 mm and the minimum distance between two neighbouring cooling channels was 0.84 mm. Starting in a direction parallel to the chamber axis, the 30 rectangular cooling channels wind around the hot gas surface. To keep the distance both to the hot gas surface and to adjacent cooling channels constant, the propagation angle of the helical cooling channels varies depending on the axial position. The helical progress of the cooling channels forces the cooling fluid to permanently change its direction and therefore increases the wall heat transfer. A separate inflow collector was necessary to ensure uniform permeability of all 30 channels.

The inspection for internal manufacturing anomalies was performed using Computer Tomography (Figure 4). Unfortunately due to relative high wall thickness as well due to the high density of the material, small imperfections in the wall structure cannot be resolved. However, channel quality can be reliably detected. This investigation allowed blockage detection of one of the cooling channels due to powder residue, which was subsequently corrected.

2. Hot firing test

The investigations presented here were performed at the European Research and Technology Test Facility P8 (Figure 5). The P8 test bench is a high-pressure test bench for subscale rocket trust chambers located at the Institute of Space Propulsion in Lampoldshausen.

Figure 5: European Research and Technology Test Facility P8, DLR Lampoldshausen

This test facility enables investigations with liquid cryogenic propellants (hydrogen, oxygen and natural gas) at the typical rocket engine operating conditions [6]. At presented experimental investigations the tested combustion chamber operated with liquid oxygen (LOX) and gaseous hydrogen (GH_2) at temperatures of 110-120 K and 150-160 K, respectively. Two configurations of the test specimen have been fulfilled. The first configuration used water as the coolant. The second configuration applied a full, regeneratively cooled combustion chamber, although only heated hydrogen from the cooling channels flowed into the injector head.

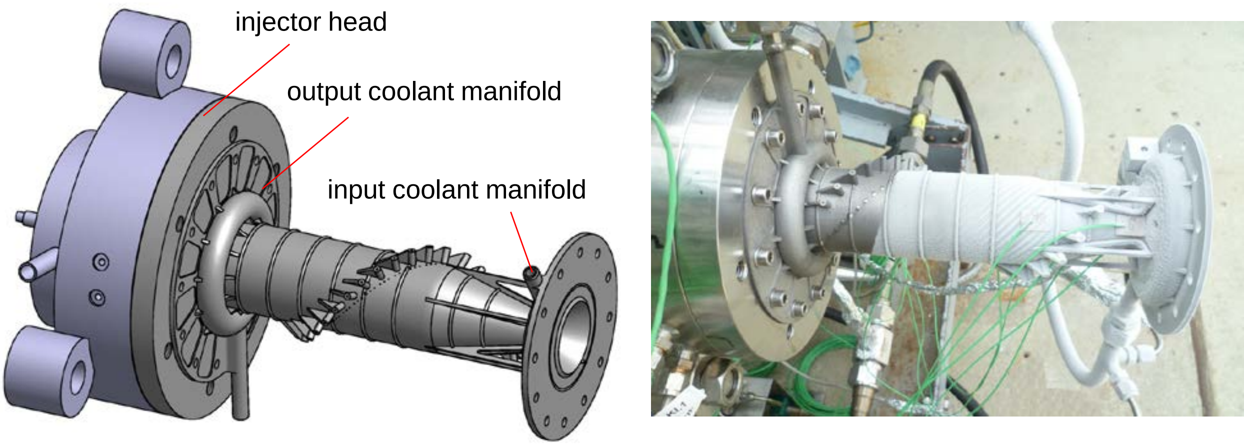
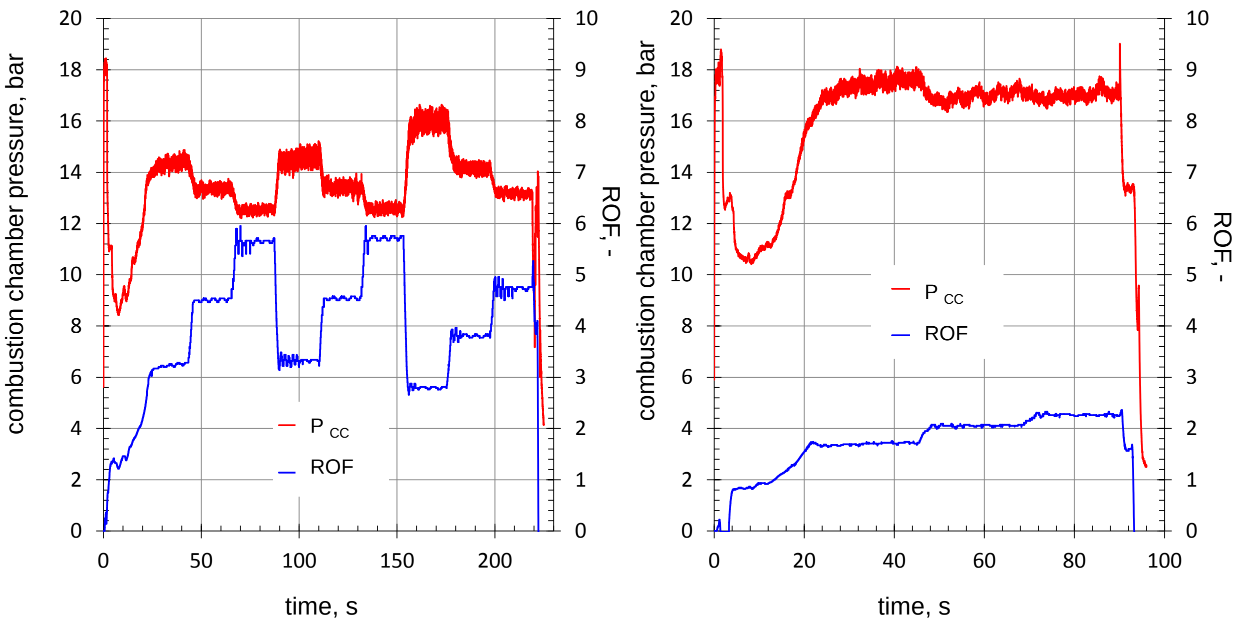


Figure 6: chamber model „K" in the test cell

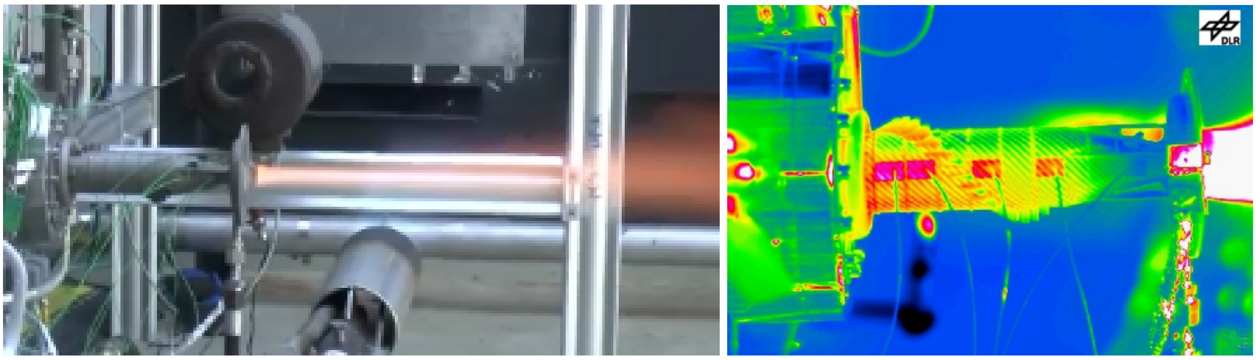
Figure 7 presents typical operating sequences which have been used to provide steady state conditions at different pressure levels and oxygen-to-fuel ratio (ROF). For better controlability, the LOX mass flow has been kept constant over all test time and only hydrogen mass flow has been varied.

The combustion chamber operated at pressures from 12 up to 20 bar and ROF from 1.4 up to 6.0. The duration of a particular load step is 20 s. This allows a stable, steady-state thermal and flow condition to be reached. Two tests with configuration 1 (Figure 8) and four tests with configuration 2 have been performed.



a) b)

Figure 7: test sequence for water cooled configuration a) and for a regenerative cooled configuration b)



a) b)

Figure 8: ALM-manufactured combustion chamber model ‘K’ during a hot firing test on the P8 test bench at DLR-Lampoldshausen; a) photograph in test cell; b) infrared image;

The influence of testing was a mechanical fatigue effect, manifesting in developing local leakage locations in the chamber wall. The tests with water cooling had shown a negligible influence on the leakage rate. During testing with the regeneratively cooled configuration, a rapid increase in the leakage rate was observed. One additional disadvantage of the regenerative configuration is a very high pressure drop in the cooling channels; up to 100 bar in tests with hydrogen as coolant.

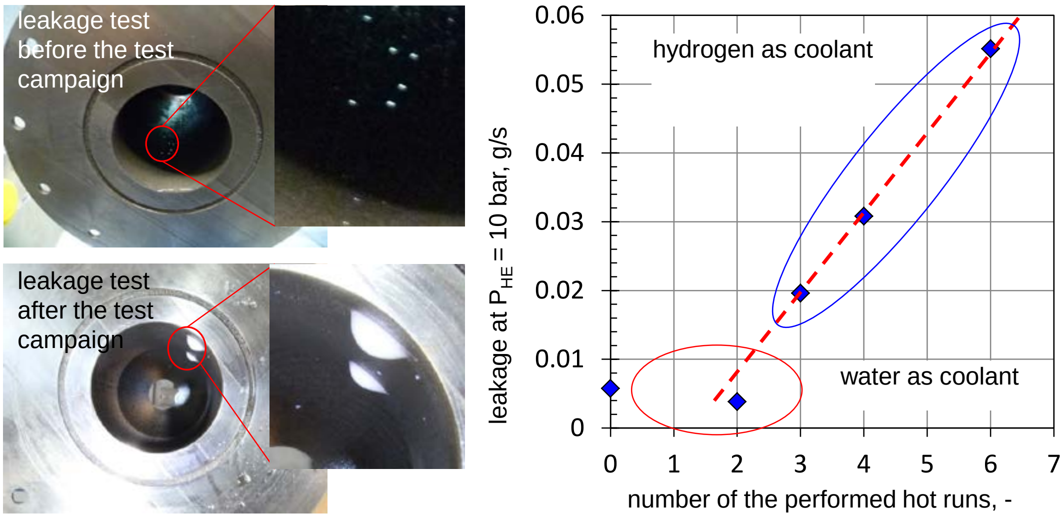


Figure 9: local leakage pattern a) and leakage mass flow evolution b)

Summary

The presented study has demonstrated new possibilities and specific features by using SLM technology for the manufacture of a regeneratively cooled combustion chamber demonstrator. While testing of the demonstrator was successful, several problems were identified, such as high pressure drop for the regenerative coolant, and a significant increase in the development of wall leakage resulting from cyclic thermal loads.

Acknowledgements

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