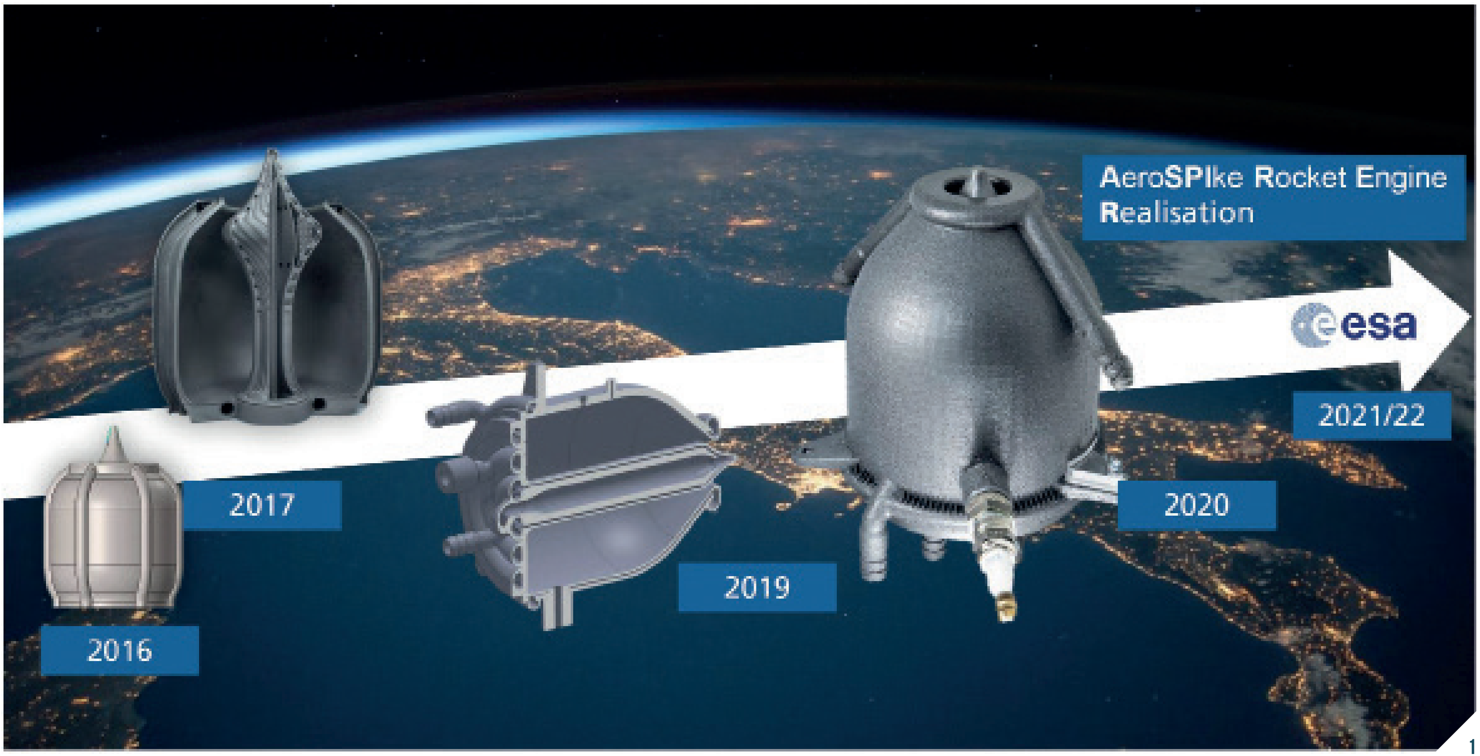


AEROSPIKE ROCKET ENGINE TESTING

Engineering dreams from the 1960s are being realized thanks to the latest manufacturing, materials and testing technologies such as Computed Tomography

// SAMIRA GRUBER, MICHAEL MÜLLER AND ELENA LOPEZ, FRAUNHOFER IWS

The market with small satellites will boom in the coming years. The UK is planning the first spaceport on European soil in the north of Scotland, and the Federation of German Industries (BDI) also supports a European spaceport.

From these spaceports small to medium-sized launchers will carry research instruments and small satellites into space. These micro launchers are designed for a payload of up to 350kg (770lbs). An efficient way of propelling these micro launchers is with so-called aerospike engines. Aerospike rocket engines have significant advantages compared to conventional engines. These include a mass-saving potential of up to 30%, a possible control of altitude and path of the launcher through secondary injection, and foremost an automatic adaption of the thrust jet in different pressure environments.

The manufacturing of the aerospike has been a challenge since the first designs emerged in the 1960s. Only recently, thanks to additive manufacturing (AM) processes is the realization of aerospike engines within reach. The Fraunhofer Institute for Materials and Beam Technology IWS and the Institute of Aerospace Engineering (ILR) at the Technical University of Dresden have started an ongoing collaboration in 2016 to design, manufacture and test aerospikes. Several design iterations were made to prove the geometrical capabilities and in 2019/2020 the first additively manufactured aerospike engine was hot-gas fire tested at a test site belonging to the Technical University of Dresden to prove the functionality of design and manufacturing process.

By using a design suitable for AM, the number of components was reduced to only two complex shaped parts: the combustion chamber and the spike with the injector head. This results in a reduction of subsequent joining steps and an enormous shortening of the process chain.

The engine is based on the combustion of a mixture of liquid oxygen (LOX) and ethanol. The two fuel components are injected into the combustion chamber via the injector head and finely atomized. An electric ignition mechanism ignites the combustion reaction in the combustion chamber. The gas expands, is accelerated along the spike to the speed of sound, exits the combustion chamber through the annular gap and gives the engine its thrust and in the case of the functional prototype, 500 N by design.

Temperatures in excess of 2400K exist in the combustion chamber during use. These temperatures are well above the melting points of most metals. This results in the need for active cooling of the engine. Water is used as the cooling medium for the developed prototype ensuring that the wall temperature of the components does not exceed 900K.

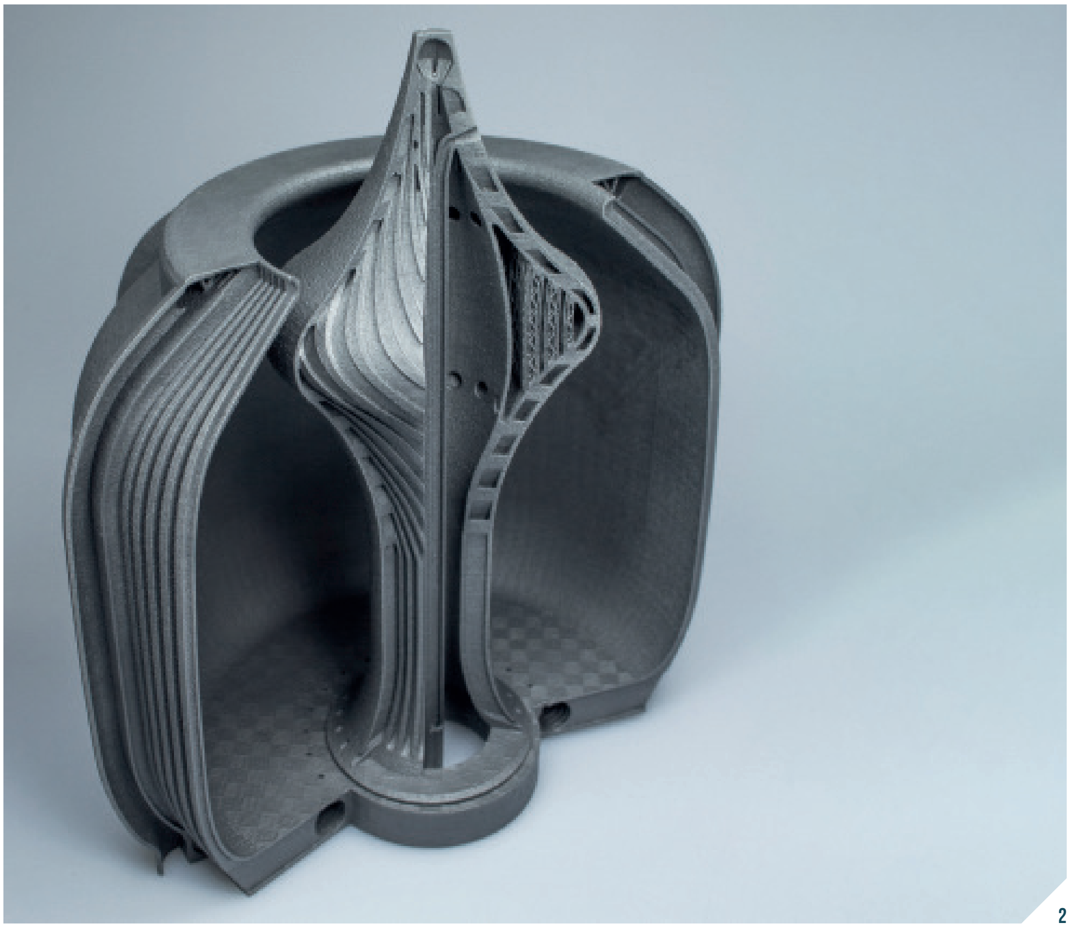
1 // Evolution of aerospike design within joint collaboration of Fraunhofer IWS and ILR

2 // Aerospike engines, geometry demonstrator

3 // Assembled test engine

MATERIALS & 3D PRINTING

INCONEL718 is an excellent material for this purpose. Compared to most iron- or nickel-based alloys, this material has excellent strength at high temperatures.



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with polymers and nozzle- based technologies for laser cladding.

The process chain for manufacturing the aerospike engine comprises of the following steps: additive manufacturing using L-PBF, mechanical post-processing like sandblasting, turning, milling, and threading, joining by laser welding, heat treatment, and component testing using computed tomography (CT).

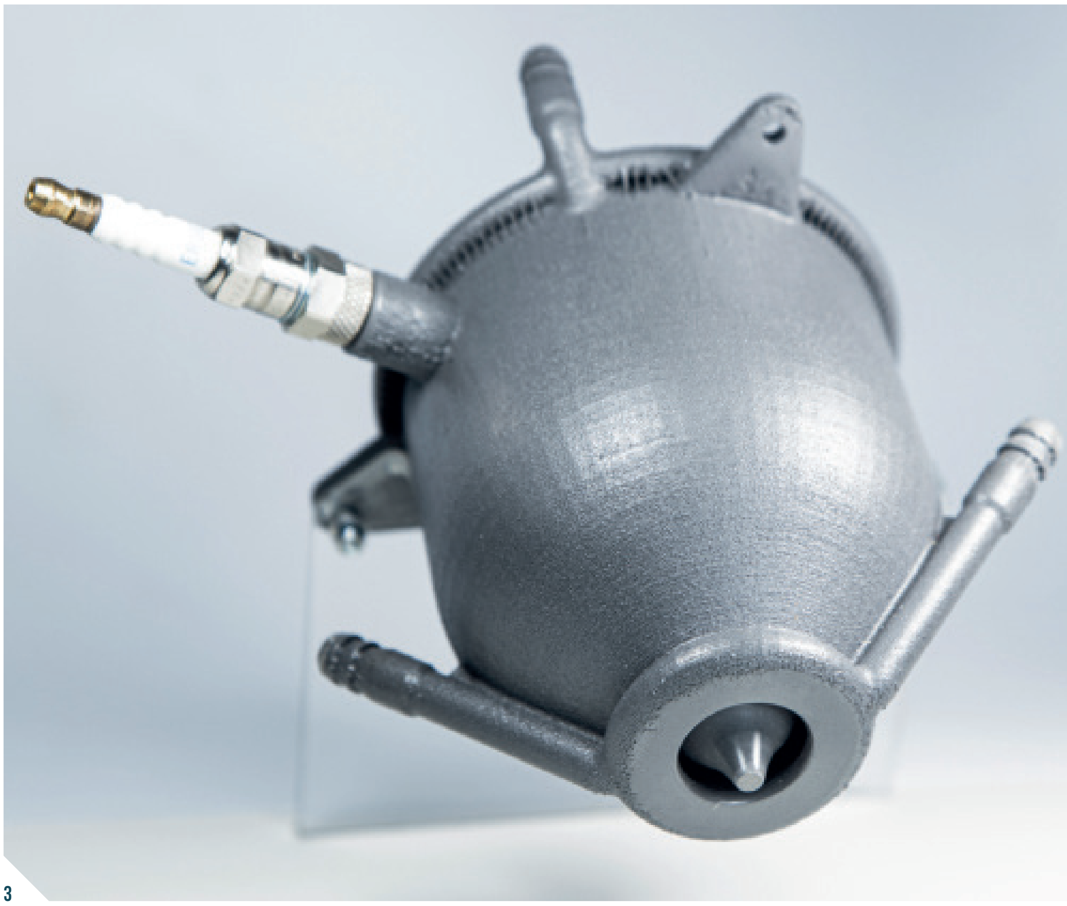
Mechanical post-processing was needed because the process-inherent roughness Ra, due to the layer-by-layer volume structure and the adhesion of powder particles ranging between 15 - 25µm, is too high for the flow and interface. Tolerances to the test stand are also insufficient right after the build job. Therefore, allowances were considered on the selected surfaces in the design. The manufacturing time for the functional engine was 48 hours and both components could be printed within one build job. Although INCONEL718 is a material well known to be used under high- temperature regimes, these properties are not available right after printing. So, a heat treatment was necessary to relieve stresses and to gain strength through precipitation hardening.

Laser beam welding is another core competence of the Fraunhofer IWS. Using a laser as an energy source, metallic components can be joined quickly and

Furthermore, INCONEL718 can be easily welded and is therefore a predestined material for processing by L-PBF. Extensive studies on the processing of this material have been carried out at Fraunhofer IWS and the process parameters have been optimized.

Laser powder bed fusion (L-PBF) is a layer-by-layer process where a laser source selectively melts fine metal powder particles. The main parameters influencing the process and the material properties produced are the laser power, the scanning speed of the laser, and the thickness of the powder layer applied. By optimizing these parameters, relative densities of over 99.5 % can be achieved. The minimum possible wall thickness and the minimum channel diameters were also tested and fed into the design. Furthermore, the surface roughness as well as the distortion had to be evaluated. The engine production was carried out on the AM 400 system from the manufacturer Renishaw.

All necessary technologies for the whole process chain including non-destructive testing (NDT) for the aerospike were available at the Additive Manufacturing Center Dresden (AMCD). The AMCD is a collaboration between Fraunhofer IWS and the Technical University of Dresden. Other available AM technologies include printing



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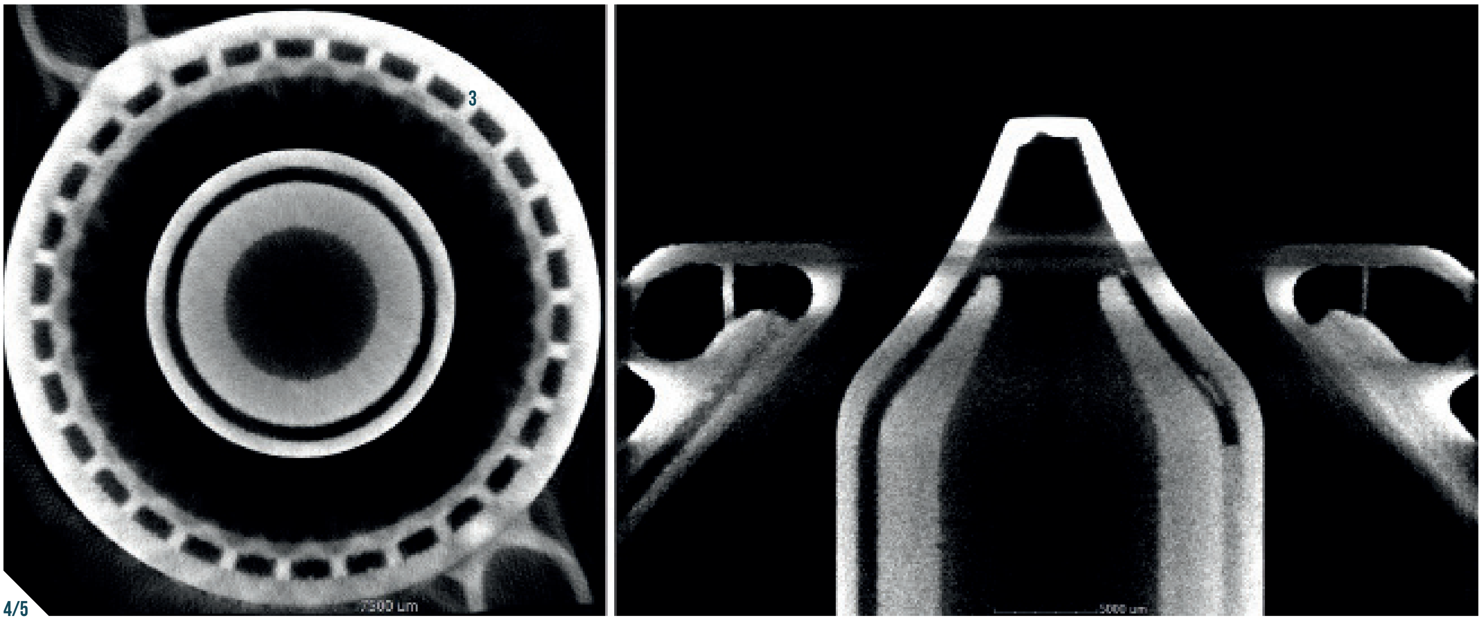

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4 // CT cross-section of the test engine with YXLON FF35 CT, top view

5 // CT cross-section of the test engine with YXLON FF35 CT, side view

6 // CT cross-section of the geometry demonstrator with YXLON FF85 CT, top view

7 // CT cross-section of the geometry demonstrator with YXLON FF85 CT, side view

with low distortion. Only a single weld seam is required to join the engine parts connecting the injector head to the combustion chamber. In the welding of pressure vessels, the IWS has built up broad know-how over many years.

Image 2 shows the geometry demonstrator design of the aerospike, with the cooling channels, the angular combustion chamber, the periodical inputs for the fuel on the outside, and the support structures in the middle needed for the stability during the build process. Image 3 shows the assembled test engine.

X-RAY COMPUTED TOMOGRAPHY

After manufacturing, it is necessary to check whether the component meets the requirements in order to avoid malfunctioning during testing. By means of CT, both the geometry demonstrator and the test engine were inspected with regards to dimensional accuracy, porosity, weld seam quality, and powder residues in cavities.

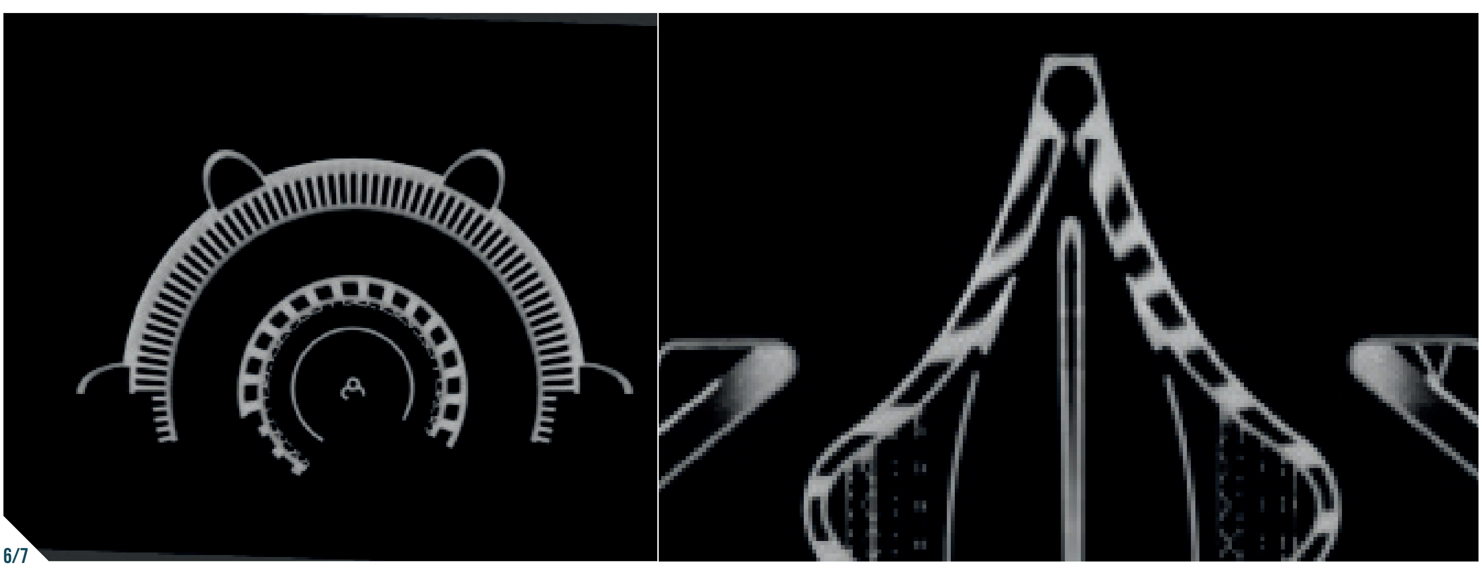
With accelerating voltages of over 200kV, an image resolution of around 25µm can be achieved for INCONEL718 at the Fraunhofer IWS using the high-resolution computed tomography system YXLON FF35 CT. But the final resolution always depends on the part dimension and maximum wall thickness. This is why the geometry demonstrator was tested at Yxlon with an YXLON FF85 CT system using 350 kV accelerating voltage and a resulting voxel size of 120µm.

The engine was tested in August 2019 at the test site of the Chair of Space Systems at the TU Dresden. By means of high-speed imaging of the engine test, the combustion was analyzed in detail. The knowledge gained is currently used to derive improvements for the further development of the engine within an ESA-funded project.

The burning and thrust was not ideal due to the insufficient quality of the printed injector holes. This will be improved in the ongoing ESA project and several mechanical post processing techniques will be tested. Nonetheless, Fraunhofer IWS and ILR from the TU Dresden could prove the feasibility and functionality of an aerospike engine.

Features such as fuel injection, near-contour cooling, or heat resistant materials are of interest for applications in toolmaking, reactor construction and aircraft engines. Therefore, the gained knowledge can be transferred, and researchers look forward to the first real flight with such an additively manufactured, efficiently burning aerospike engine, qualified via non-destructive testing methods.\\

Samira Gruber, Michael Müller are researchers and Elena Lopez head of division at Fraunhofer IWS



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