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Design and Testing of Liquid Propellant Injectors for Additive Manufacturing

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Abstract
As other aerospace companies worldwide, Airbus Safran Launchers is developing injectors for its current and future liquid rocket engines using additive manufacturing. In order to introduce this new manufacturing technology without compromise on reliability on existing engines, a stepwise approach was pursued in the past years to develop all capabilities to design, manufacture and operate liquid rocket engine injectors made by additive manufacturing. In this technology development, all design and manufacturing steps were taken into account, starting from material characterisation and updating the design tools where necessary, to simple single element screening tests before designing, manufacturing and hot fire testing different injector configurations to increase the technology readiness level for implementation on existing liquid rocket engines. Additionally, the research activities aim at fully capitalising on the possibilities offered by additive manufacturing for future liquid rocket engines, where as of today design is not yet fixed and allows for a more comprehensive approach without additional justification and qualification effort.

Abbreviations & Acronyms

AM	Additive Manufacturing	FEM	Finite Element Method
c_D	Discharge Coefficient	GH2	Gaseous Hydrogen
CFD	Computational Fluid Dynamic s	LCH4	Liquid Methane
CT	Computer Tomography	LOX	Liquid Oxygen
DLR	German Aerospace Center	NDI	Non-Destructive Inspection
EB	Electron Beam	SLM	Selective Laser Melting

1 Introduction

The advantages offered by additive manufacturing of liquid rocket engine injectors seem obvious: Optimised design capabilities allow for a reduction of mass and an improvement of the injector's performance. A reduction in individual piece parts, manufacturing and integration steps allows for a significant reduction in manufacturing cost and lead time of liquid rocket engines. For this reasons, additive manufacturing has attracted a lot of interest of manufacturers of liquid rocket engines [1] - [6].
Being integrated from numerous piece parts, which are manufactured to tight tolerances and inspected meticulously after every manufacturing step, the injector head is one of the key components of a liquid rocket engine. Whereas the larger parts like the manifolds typically are machined from a cast raw part, the individual injection element piece parts are machined from forged bars and the soldered or welded to the manifolds. The casting process limits the minimum wall thickness of the components, which prevents consequently lightweight designs. Furthermore, an optimised design, which carries the mechanical and thermal loads during operation, would imply additional machining steps and therefore additional cost in a conventional manufacturing process, while the brazing of forged parts constraints the design as well. Although the posts and sleeves are machined automatically on numerically controlled machines, integrating several hundred of injectors into a full injector head implies a lot of manual work, which implies additional cost during the manufacturing process.

Additive manufacturing can provide significant benefits, as it allows for a more flexible design of structures and reduces the number of individual parts and the integration steps needed to finish the product. However, several technical issues need to be controlled in order to provide a robust and reliable injector design which reduces engine cost, but not engine reliability. A sound material data base is as indispensable as a rigorous cleaning and inspection processes to guarantee the high quality of the manufactured parts.

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In parallel to establishing the data base on manufacturing parameters and material properties, Airbus Safran Launchers stepwise started with manufacturing and flow checking of individual injector elements, which were used to investigate the limits as well as the reproducibility of the additive manufacturing process with respect to small orifices and delicate structures. Having successfully demonstrated the feasibility to build up the delicate injector geometry with additive manufacturing to meet the fluid-mechanic requirements, subscale hot firing tests were performed to compare the performance characteristics of these injectors to classical benchmark hardware. The subscale hot firing test campaign confirmed the robust design of the injectors and showed that additive manufacturing does not negatively impact the injector's performance.

Having completed this development step successfully, everything is ready to introduce additively manufactured liquid rocket engine injectors on the propulsion systems of the Ariane 6 launcher, which is scheduled for maiden flight in 2020. For the gas generator of the Vulcain 2.1 as well as for the thrust chamber of the Vinci upper stage engine, designs were established which meet the engine requirements in form, fit and function and can be introduced with minimum qualification effort. While the development of additively manufactured liquid rocket engine injectors on the basis of a "copycat" design is proceeding as planned, the lessons learned are applied to studies and demonstrator engines which in the future shall fully capitalise on the advantages offered by additive manufacturing.

1.1 Manufacturing Process Chain in Additive Manufacturing

To properly master the process of additive manufacturing of any part, the entire process chain of additive manufacturing needs to be considered during the technology development process. Figure 1 illustrates the wide scope of technology development activities which need to be addressed, comprising even such seemingly obvious and simple processes like machining and welding of alloys made by additive manufacturing. Obviously, the selection of the raw powder in its chemical composition as well as in its powder particle size distribution or its flowability significantly influences the material properties of the final part. The printing strategy on the other hand affects the material properties as well as residual tensile stresses in the printed part and can be used as a measure to minimise the printing time and hence manufacturing cost. Depending on the application requirements, surface treatment processes need to be applied to improve the surface finish, to ensure compliance with stringent cleanliness requirements or to make non-destructive inspection results interpretable.

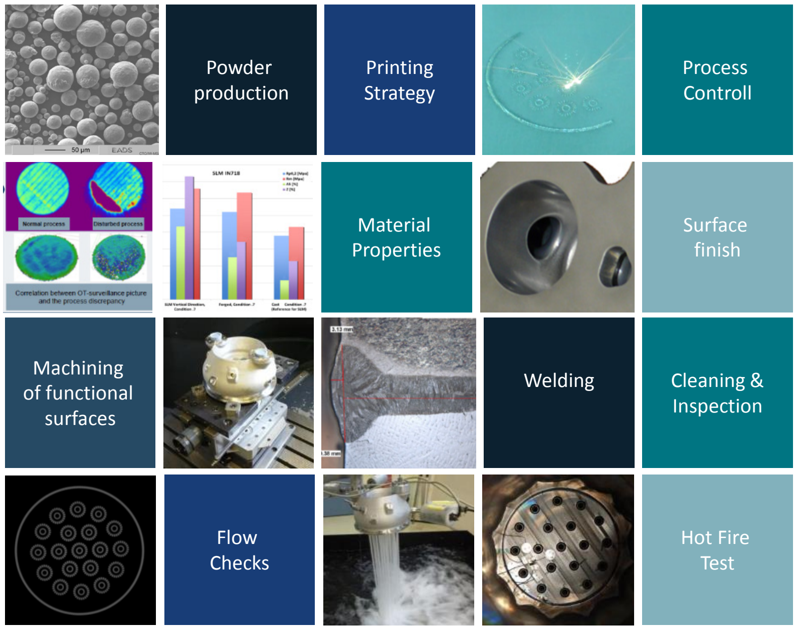

Figure 1: Technology development fields of the additive manufacturing process chain

For later integration, the machining of functional surfaces needs to be managed as well as the welding of the additively manufactured part when it shall be joined with other parts. Moreover, during the assembly and integration activities, non-destructive inspection needs to be applied to make sure that the parts meet the cleanliness and tightness requirements for a later application in a liquid rocket engine. Compared to the classical manufacturing process, where every single piece part can be checked thoroughly before integration, flow checks, endoscopic inspection and computer-tomography are used to check the quality of the parts.

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1.2 Injector Development Logic

In general, two different development logics can be applied when developing injectors for liquid rocket engines - either there is an existing design, which is adapted to additive manufacturing, or the injector is designed from scratch taking into account only requirements and constraints for installation, integration and performance.
Regardless of which approach is used, any injector development follows a development logic as illustrated in Figure 2. It starts with a full scale design concept, from which single element injectors are manufactured to characterise the injector's hydraulic behaviour and to identify how accurately and reproducible the functional geometries like orifices or small-sized annuli can be manufactured.
The single injector flow checks, which typically use water or gaseous nitrogen as substitute fluids, are subsequently used to design a subscale injector which is used for fire tests. Here, the injector is subjected to the full life cycle of thermomechanical loads like in the later real application. The last step is the manufacturing of a full scale injector, which is again flow checked and inspected before being operated in an full scale setup. In parallel to this manufacturing and testing steps, all required engineering disciplines which are needed to fully control and exploit the benefits of this manufacturing technology are being matured (see Figure 2, bottom).

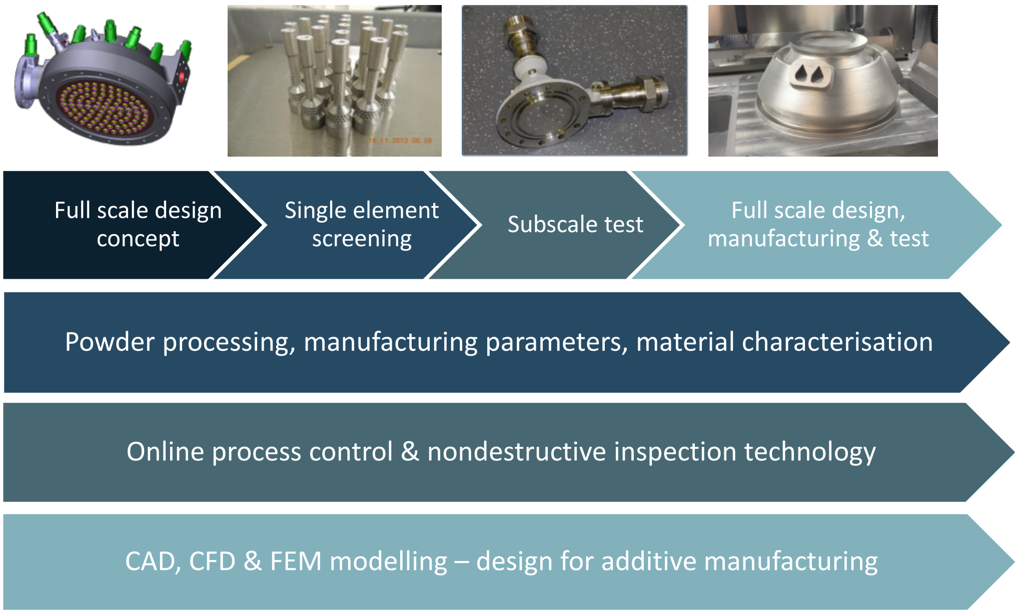

Figure 2: Additive manufacturing injector development logic

2 Development & Demonstration Activities

The following sections provide some more information on the individual development and verification steps.

2.1 Material Characterisation

The data base for the justification of the design of lightweight liquid rocket injectors was established during a material characterisation program, in which specimens were tensile tested in inert as well as in hydrogen atmosphere at different temperature levels and with powder coming from different lots. Figure 3 shows results of this characterisation programme for Inconel 718 and gives a qualitative comparison of the material data with tensile test specimens made from cast and forged material, respectively.

Compared to samples made from cast materials - which are typically used for injector manifolds - the levels of tensile strength and ultimate yield strength are approximately 20% higher for additive manufactured samples, giving additional potential for weight savings in the later design. Compared to samples made from forged bar, there is a slight increase in material properties for the additively manufactured samples. The anisotropy of the material properties was found to be negligible for engineering purposes thanks to dedicated heat treatment procedures.

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While the ongoing development programmes use the results of this material characterisation programme, research activities are ongoing in parallel to investigate how the microstructure material made by selective laser melting can be improved further taking into account the effect of the powder raw material, the laser scanning strategy and the heat treatment process applied for precipitation hardening of alloys. Here, a cooperation with academia and research institutes provides expertise in this field of research [7].

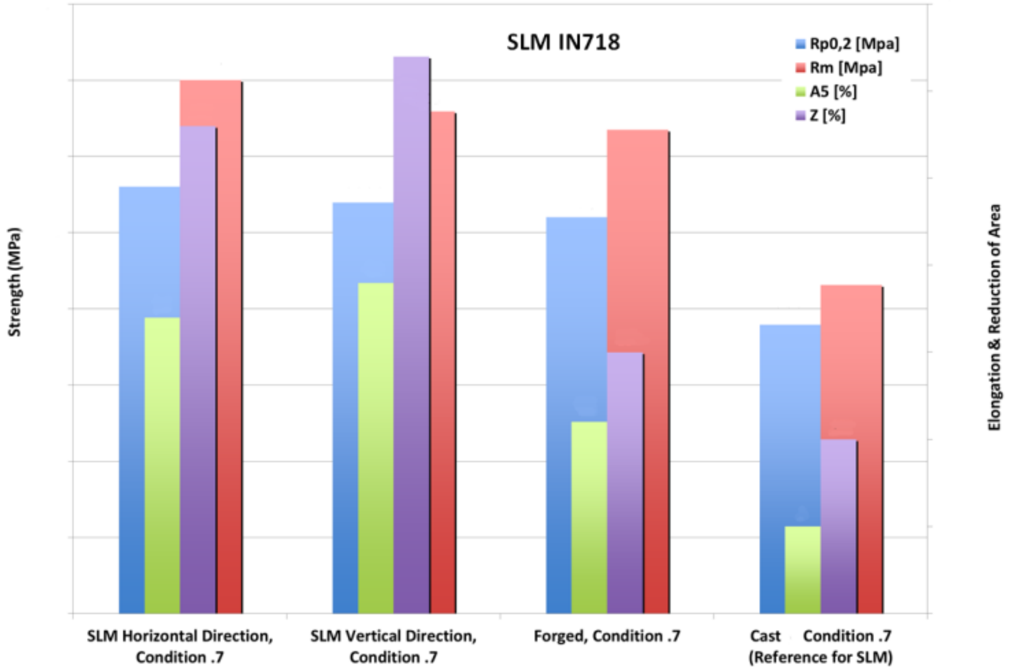

Figure 3: Results for material properties of heat-treated Inconel 718 made from additive manufacturing compared to forged and cast samples

Other mechanical data such as High Cyle Fatigue, Low Cycle Fatigue, crack propagation and fracture toughness of Inconel 718 at various temperatures have also been conducted. All data are in a statistically acceptable range when compared with justification requirements.

2.2 Single element characterisation

Single element injector flow checks were used to confirm the transfer of the classical injector design to an additively manufactured injector. Here, the effect of the increased wall roughness needs to be taken into account as well as the fact that small orifices which are used to set the injector pressure drop and ensure a homogeneous flow cannot be printed with the same accuracy as they would have if manufactured by precision turning and milling. Additionally, the flow checks can be used to assess how reproducible the injector characteristics are at different locations in the build chamber, where locally different boundary conditions of heat impact, gas flow and laser optics may affect details of the manufactured parts. Comparing production samples later on from the different manufacturing batches of the injectors allows monitoring the stability of the manufacturing process from batch to batch.

As mentioned before, the flow checks typically use water or gaseous nitrogen as substitute fluid for the propellants. To more accurately fit the Reynolds number, of the water in comparison to liquid oxygen, heating of the water may be considered to set its viscosity. The flow check setup, which is equipped with an optical accessible chamber, allows imposing a back pressure of up to 50 bar in order to correctly mimic the engine backpressure during operation and to investigate potential cavitation margins of the injector. In the experiments, the mass flow rate is set such that the Mach and Reynolds number are comparable to the expected hot fire operating conditions.

With the single element flow checks it could be demonstrated that not only coaxial shear injectors can be manufactured with sufficient accuracy, but also coaxial swirl injectors, which are used commonly with hydrocarbon propellant combinations can be designed for additive manufacturing. As an example, Figure 4 illustrates the spray pattern from a simplex LOX/LCH4 injector which was designed using the results of a classical injector design approach and transferring these to a design which can be 3D printed and which anticipates the effect of wall surface

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roughness on the spray behaviour. The tests were performed using water as substitute fluid. As can be seen from the comparison of the still images, there is virtually no difference in the spray angle of the printed injector and the classically manufactured injector.

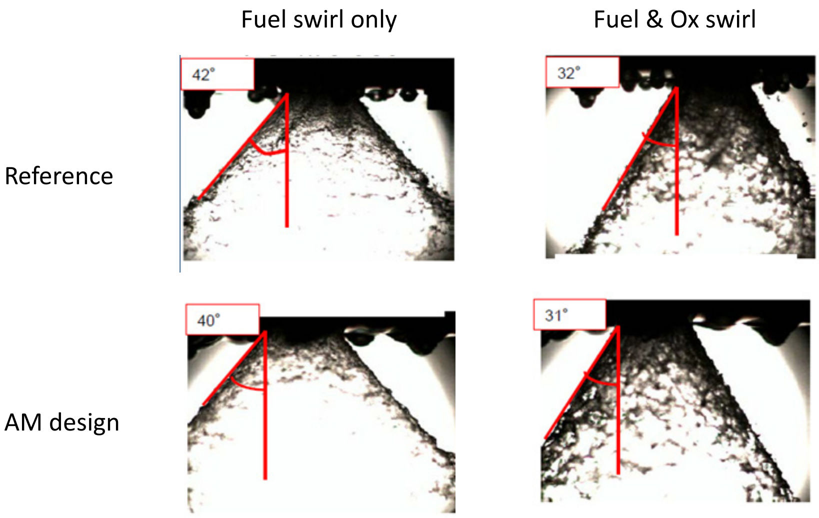

Figure 4: Flow check results for coaxial swirl injectors - comparison of spray angles from machined (top) and printed (bottom) injectors

The first flow check experiments performed on coax shear injectors were also used to confirm the possibility of avoiding any additional post-treatment like turning, abrasive flow machining or chemical polishing, which may be used to improve the surface finish. Figure 5 illustrates the coax shear injector samples, their relative position on the building platform and the discharge coefficient recorded on the LOX side. Data recorded in numerous tests justifies the obsolescence of any of these surface finishing processes for liquid rocket injectors. With a bench reproducibility of 0.2%, the overall scatter in the calculated discharge coefficient was below 3% for the fuel injectors and below 4% for the oxygen injectors. No correlation was found with respect to the location at which the injectors had been built up in the powder bed.

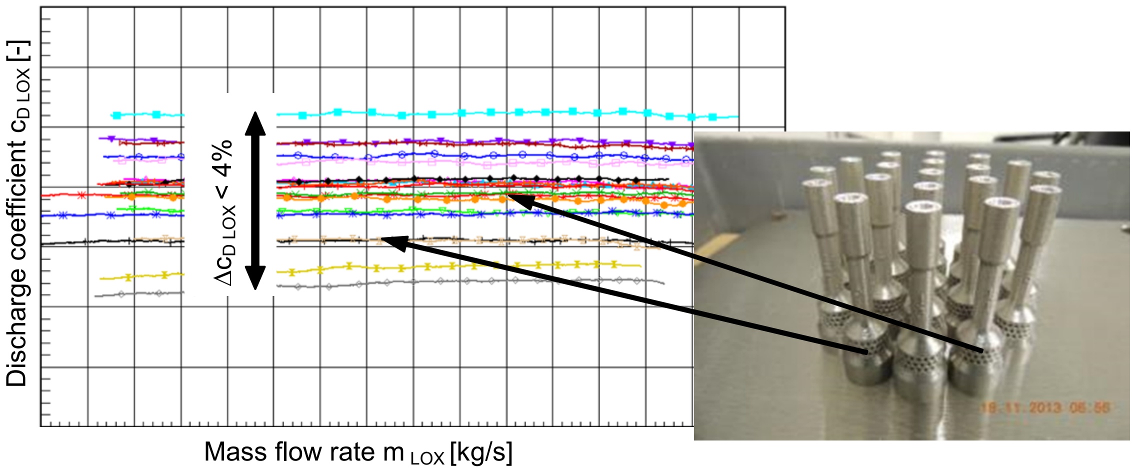

Figure 5: Discharge coefficient for additively manufactured injectors from one batch

2.3 Subscale Testing

Subscale testing of injector configurations provides detailed information of the performance of an injector and can be used to compare the characteristics of an additively manufactured injector with a classically machined one. Within the scope of R&T programmes, several subscale injectors for an expander-cycle rocket engine have been manufactured and hot-fire tested in nominal operating conditions.

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The first tests were performed at DLR's research and development test facility P8 in Lampoldshausen using liquid oxygen (LOX) and gaseous hydrogen (GH2). The tests used a calorimetric water cooled subscale combustion chamber with a chamber diameter of 80 mm. The experiment was designed to directly compare the two injectors on the same hardware setup within one test campaign. This enables a comparison of the 3D-printed injector's performance data with the classical design and manufacturing route like injector pressure drop, heat release evolution, combustion efficiency and combustion stability. Both injector configurations could be installed in the identical set of fuel and oxidiser manifold. The 3D-printed injector cartridge was made of Inconel 718. Test data was recorded in a combustion chamber pressure range from 35 bar to 81 bar and with a propellant mixture ratio ranging from 4.4 to 7.1.

A comparison of the heat release profile and the combustion efficiency recorded during the test shows no difference for the additively manufactured and the classically manufactured benchmark injector. Due to differences in the manifold design, the pressure drop of the 3D-printed injector was higher than in the benchmark hardware. As the overall pressure drop can easily be tuned by slight design modifications without changing the other injector characteristics, the subscale test results marked a successful achievement of this technology development step.

For the following test campaign, the level of design complexity was increased and an integral injector head was hot fire tested. This injector is illustrated in Figure 6. It comprised not only the injectors themselves but also included the manifolds for fuel and oxidiser. Different from the insert that was tested during the preceding test campaign, this injector used stainless steel 1.4401 (also known as 316L) as material. This design also provided valuable information on the inspection and cleaning procedures to be applied during the manufacturing process. As a direct optical inspection of the individual injectors is not possible in this setup, endoscopic inspection and CT scanning were used to check the status of the injector before commissioning it for hot fire testing. Having hot fire tested this part successfully; sufficient experience has been gained for both Inconel 718 and stainless steel 316 L to transfer the know-how to full-scale injectors for different applications.

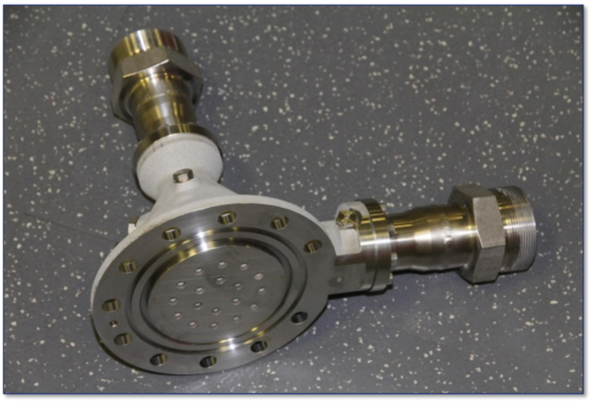

Figure 6: Subscale integral injector manufactured from stainless steel 316L

2.4 Full Scale Demonstrators

The injector of the Vulcain 2 gas generator was selected for the introduction of additive manufacturing on a full scale engine. For this application, the design of the additively manufactured injector needs to comply with the requirements on form, fit and function to 100%, i.e. the design parameters of the injectors like recess length, orifice diameters etc. itself remain unchanged and the interfaces of the injector to the feed valves, the ignition system and the gas generator combustion chamber are identical to the current flight hardware.

In a first design loop, the injector was built using the selective laser melting process without applying significant modifications to the geometry of the part. This design can be used on a gas generator system without any changes on the combustion chamber or the injector valves of the gas generator. Figure 7 shows the injector in detail and installed on the gas generator hardware on the P8 test facility. In parallel, a technology study was performed to explore the additional potential in cost saving and performance increase when relaxing some design constraints. Figure 7 shows the differences to the former design, which drastically can reduce the time needed for manufacturing, but requires also a redesign of the gas generator combustion chamber interface. Both injectors were hot fire tested successfully in 2015 and 2016. Currently, a 3D-rpinted injector head is being commissioned for acceptance testing for the later use on Ariane 6.

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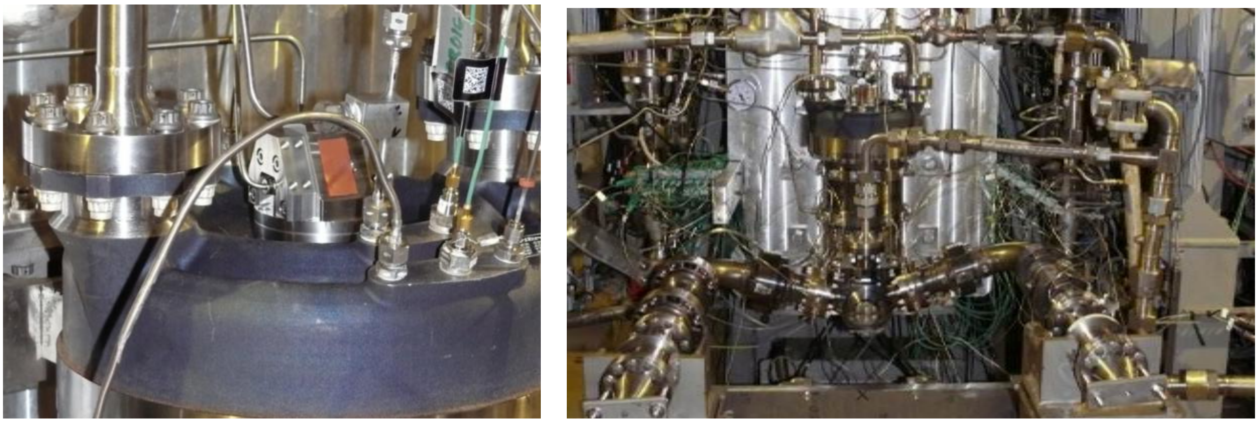

Figure 7: Additive manufactured injector installed on Vulcain 2 gas generator at P8 test facility

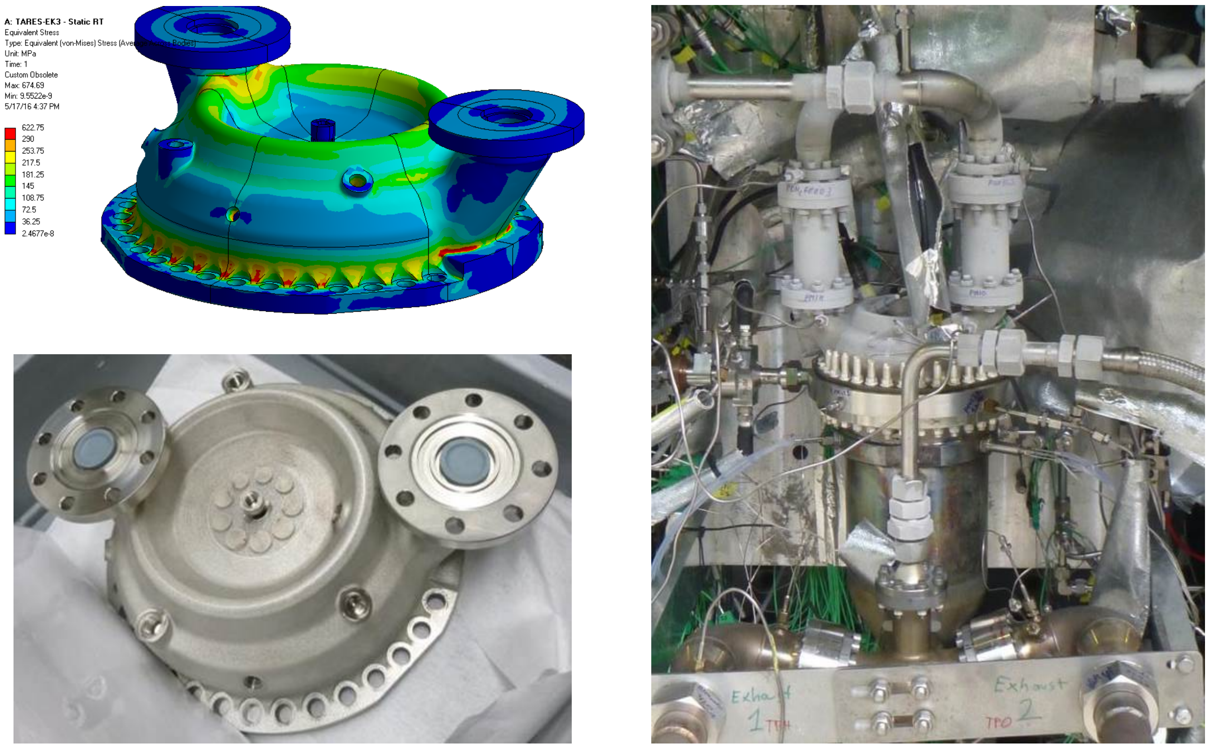

Figure 8: Redesigned gas generator injector for Vulcain 2.1 application

In parallel to the Vulcain gas generator, the thrust chamber injector of the Vinci engine was investigated with respect to the possibilities to apply additive manufacturing on a larger injector. Thrust chamber application expander cycle - design study for Vinci - cartridge solution due to size of injector. Currently, there are no direct metal laser sintering machines available which would allow a production of an integral injector of this size on a machine qualified for the production of actual flight hardware. While such manufacturing capabilities are currently being installed at Airbus Safran Launchers, technology demonstrators were designed and manufactured for a so called "cartridge" design, in which an array of injectors is printed and welded to the propellant manifolds subsequently. Figure 9 illustrates the location of the cartridge within the injector assembly and shows a hardware sample of a printed injector cartridge. Different from the classical design, the fuel and oxidiser injectors are manufactured from one single piece with the thread for the fixation of the injector faceplate being printed. This design allows for an easy inspection and cleaning of the injectors, as the face plate is installed separately, once the injector cartridge is welded to the propellant manifolds.

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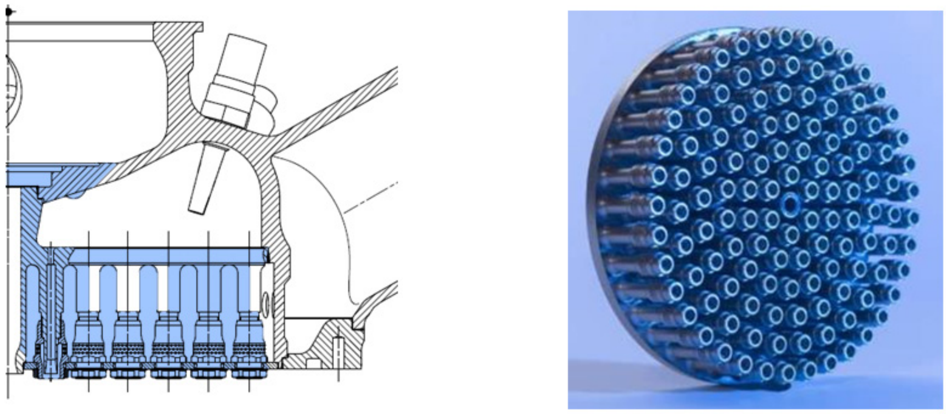

Figure 9: Vinci injector cartridge: integration concept (Left) and manufacturing sample (right)

While having the potential to quickly be introduced into a Vinci engine, the cartridge design does not make full use of the potential in cost reduction which an fully integral design would allow. To assess the optimisation potential and the additional reduction in cost which could be achieved with an integral design, a full scale concept of an integral injector was established. Different manifold topologies were investigated with respect to their manufacturability and the uniformity of the propellant flow in the manifolds (see Figure 10).

In parallel, a demonstrator hardware was designed and manufactured to test the manufacturability of such a large integral injector on an EOS M400 selective laser melting machine. The focus of this demonstrator was to verify the geometrical accuracy of such a large injector and to check the feasibility to comply with the cleanliness requirements of the part. The concept and the manufactured hardware are shown in Figure 11.

Figure 10: Studies for the design of propellant manifolds for an expander engine injector

Figure 11: Full scale manufacturing demonstrator for an expander engine injector

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While the process of additive manufacturing has been matured for flight application for classically designed coax-shear injectors in the last months and is now being transferred to production of actual flight hardware, R&T activities focus on the sue of this manufacturing technology for alternative injector concepts.

For example, Figure 12 shows the CFD simulation of the design of an integral injector for a LOX-LCH4 injector of a gas generator which uses coax swirl injectors. The injector concept itself has been tested extensively for its use on a 350 kN gas generator engine in 2013 and has demonstrated its good performance and exceptional throttling capability [7]. Within an R&T project, Airbus Safran Launchers has transferred the design of the injector, in which formerly seven individual injectors were high-precision machined and EB-welded to the manifolds, to an integral injector design. Again, the same development logic as described above has been applied: Single element flowchecks were used to verify the key design parameters of the individual injectors (see also Figure 4); subsequently, the design of the entire injector was investigated using CFD and FEM tools. For example, the right image in Figure 12 shows a CFD simulation of the fuel manifold. The injector is currently being machined and will be put to hot fire test in autumn 2017. Figure 13 shows a still image from the flow checks performed during the manufacturing and integration process.

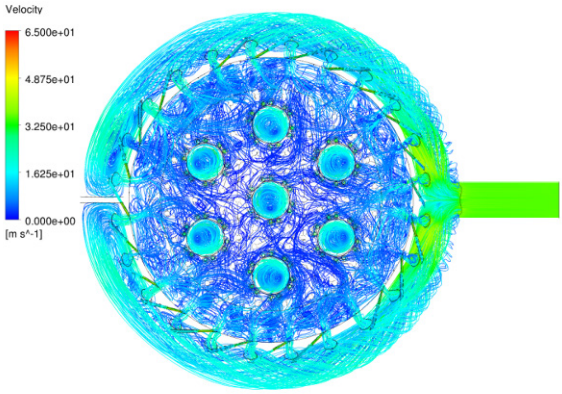

Figure 12: LOX-LCH4 gas generator injector with swirl injectors: CFD simulation of fuel manifold

Figure 13: Flow check of full scale LNG gas generator injector

Another field of activities investigates the possibility to realise radically new designs and spatial configurations of injectors using additive manufacturing. Thanks to the freedom in designing parts which is provided by additive manufacturing, new shapes of injectors are possible, which so far would have resulted in a drastic increase in manufacturing cost and which were hence not realised. When using the additive manufacturing process, these designs can be realised without any additional cost.

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3 Conclusion

Airbus Safran Launchers pursues a comprehensive approach to apply additive manufacturing to liquid rocket engine injectors. The research and technology activities performed so far address the entire manufacturing process, from powder and material properties up to design concepts to non-destructive inspection technologies to allow for the adequate quality assurance to be applied in later production. With a stepwise approach to demonstrate the maturity of the processes, Airbus Safran Launchers has matured the technology to a status where further qualification and application into flightworthy components for use on Ariane 6 can be performed. In parallel to implementing the technology on the new Ariane 6 launcher, the technology is further investigated within research and technology programmes to fully exploit the capabilities of this manufacturing technology.

4 Acknowledgements

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