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Additive Layer Manufacturing Technology In Avio Injector Head Design

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Abstract
In the frame of research activities, AVIO S.p.A. is striving for high effort to develop new concept of injector head based on additive layer manufacturing (ALM) for the new cryogenic engines development for Vega-E application. This research activity was born to exploits the new benefits coming from the new manufacturing technology, overcoming some of the limits that have been always met in the past history of rocket engine development.
Different concepts and architectures have been analyzed and produced by Powder Bed Fusion technology. Several experimental tests have been successfully accomplished.
The tests campaign involved firstly cold flow tests of both single injector element and full injector heads, and then several firing tests of the full injector heads themselves. The benefits of the new technology have been assessed and new technological solutions to overcome the ALM drawbacks have been implemented.

1.Introduction to ALM Processes

Additive manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining [1].
The basic principle is that material is continuously added by melting metals powders, to obtain a fit-for-purpose hardware, as opposed to classical processes, where it is machined away from larger, semi-finished products.
The two main parameters of any metal AM process are type of input raw material and energy source used to form the part [2]. Input raw material can be used in the form of metal powder or wire whereas laser/electron beam or arc can be used as energy source as shown in Figure 1.
AM machine requires CAD model of the part in 3D specific file format. Specialized slicing software then slices this model into number of cross sectional layers. AM machine builds these layers one by one to manufacture complete part [3]. Thickness of these layers depends on the type of raw material and the AM process used to realize the given part. Every AM manufactured part has inherent stair case like surface finish due to layer by layer build up approach.
Metal AM processes can be classified into two major groups, according to material feeding:

- Powder Bed Fusion (PBF), where the powder is drawn in successive thin layers which are then scanned by a source of energy (e.g. laser beam);
- Directed Energy Deposition (DED), where the powder is deposited by means of nozzle into the molten pool, also established by a laser.

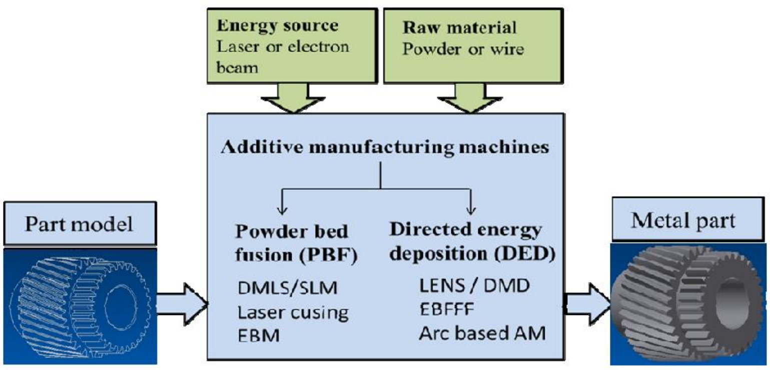

Figure 1: Common metal additive manufacturing process [4,5]

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Both of these technologies can be further classified based on the type of energy used.
In PBF based technologies, thermal energy selectively fuses regions of powder bed [1]. Selective laser sintering/melting (SLS/SLM), laser cusing and electron beam melting (EBM) are main representative processes of PBF based technologies.
In DED based technologies focused thermal energy is used to fuse materials (powder or wire form) by melting as they are being deposited [1]. Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Electron Beam Free Form Fabrication (EBFFF) and arc based AM are some of the popular DED based technologies.
Build time required to complete a part in PBF based technology is more compared to DED one, but higher complexity and better surface accuracy can be achieved, so that less machining post-processing is required. The advantages of PBF technology meet the needs of rocket engine components (e.g. high complexity due to internal channels) and pushed AVIO to spend high effort to realize and test some of the main components by means of PBF technique. Moreover, even though EBM technology has many advantages (e.g.: higher build rates), the PBF laser based technology (DMLS, SLS/SLM, laser cusing) has been adopted thanks to its lower machine cost, high accuracy and availability of larger build up volumes, more suitable for rocket engine components dimensions.
In particular, this work is focused to the results achieved by AVIO in manufacturing Injector Head by means of ALM technique.
The machines used for ALM manufacturing come from the following manufacturers: EOS, Renishaw and Concept Laser.

2. Injector Head : Additive Layer Manufacturing vs Traditional Technology

Among the subsystems of a rocket engine, the “heart” of the engine is the Thrust Chamber, in which exothermal combustion reactions take place; its geometry is such to allow the best achievable performances, by also ensuring the correct cooling of its walls in order to heat up part of the fuel which will let the turbomachines work.
The main aims of the Thrust Chamber are here below listed:

- To ignite and burn the propellants;
- To produce the required thrust during time;
- To transmit the thrust to the structure of the stage;
- To ensure the chamber temperature within acceptable values by means of the cooling system implementation;
- To ensure the minimum hydraulic resistance within the cooling channels.

The Thrust Chamber is composed by two main components:

- The Injector Head, which has the scope to inject the propellants within the combustion chamber in such a way they are properly atomized and mixed for the combustion reaction; this scope is referred to a proper number of injectors that are designed and distributed in such a manner to guarantee the most homogeneous atomized flow at the combustion chamber inlet. Moreover, they are designed to reduce as much as possible the pressure losses, by ensuring at the same time stable combustion process.

- The combustion chamber, where the exothermal combustion reactions take place; its geometry is optimized to guarantee both the correct walls cooling and the required heating of the coolant;

The main reasons for applying ALM in the components manufacturing, instead of traditional technology, are further explained:

- **Increase performance**
    - Reduce mass (light weight construction, resource efficiency);
    - Increase efficiency (combustion processes, free formed surfaces/channels);
    - Integrate closed, complex internal channels (e.g. injectors geometry);

- **Simplify production and increase production safety**
    - Integration of numerous functions in one single component without assembly efforts;
    - Even complex objects will be manufactured in one process step;

- **Rapid Manufacturing**
    - No need for special tools: direct production possible without costly and time-consuming tooling;

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- No need for long-lead procurement of billet material;

- **Complex shaped parts**
  - Allow the alternative design / manufacture of parts requiring machining of more than 80 % of the initial material;
  - Increasing object complexity will increase production costs only marginally.

Some drawbacks for applying ALM exist and are listed here below:

- **Part size**
  In the case of powder bed technology, the part size is limited to powder bed size;

- **Production series**
  The AM processes are generally suitable for unitary or small series and is not relevant for mass production. But progresses are made to increase machine productivity and thus the production of larger series. For small sized parts, series up to 25000 parts/year are already possible;

- **Part design**
  In the case of powder bed technology, removable support structures are needed when the upper layer does not have any base to be fused;

- **Material choice**
  Though many alloys are available, non weldable metals cannot be processed by additive manufacturing and difficult-to-weld alloys require specific approaches;

- **Material properties**
  Parts made by additive manufacturing tend to show anisotropy in the Z axis (construction direction). Besides, though densities of 99.9% can be reached, there can be some residual internal porosities. Mechanical properties are usually superior to cast parts but in general inferior to wrought parts. Moreover, the roughness of surfaces is higher than that obtained by a traditional technology.

3. Technological Aspects: benefits of ALM in Injector Head Manufacturing

As explained in the paragraph 1, the ALM process adopted by AVIO for ALM implementation is based on PBF (Powder Bed Fusion) technology, in particular on laser process (DMLS, SLS/SLM, laser cusing).
The Injector Heads build up by means of traditional technology were typically characterized by a large number of parts, jointed each other through welding or brazing process.
A typical product was so composed:

- 80 about single elements;
- 1 brazing joint in the critical joint (fuel/oxidizer interface);
- 8 welding joints for the propellants and pressure ports, as well as for the internal parts to be joined.

The innovative ALM Injector Heads realized by AVIO are instead so composed:

- 2 single elements: main body and firing plate;
- No brazing joints in the critical joint. So no leak of any propellants can occur at fuel/oxidizer interface;
- No welding joints, that can represent a weak point of the structure;

3.1 First Implementation of ALM on Injector Head manufacturing

Concerning the first Injector Head made in ALM, the main body was made by 2 parts in Inconel 718. This splitted implementation was set according to both a step by step process, by moving from traditional technology (a lot of parts) to ALM technology (few parts), and to guarantee a correct cleaning of all LOX volumes.
In this way the Injector Head was so composed by 3 parts:
1) ALM LOX Dome;
2) ALM CH4 Dome;
3) Copper Alloy Firing plate based on traditional manufacturing technology.

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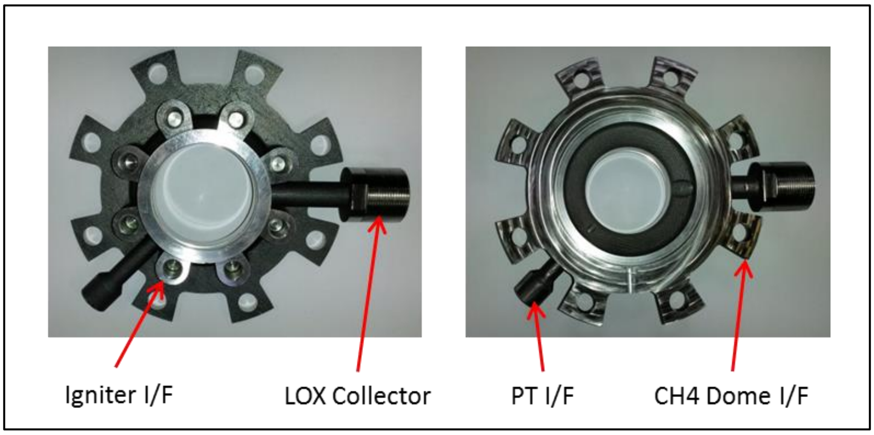

Figure 1: LOX Dome seen from external and internal sides (respectively at left and right side of the figure)

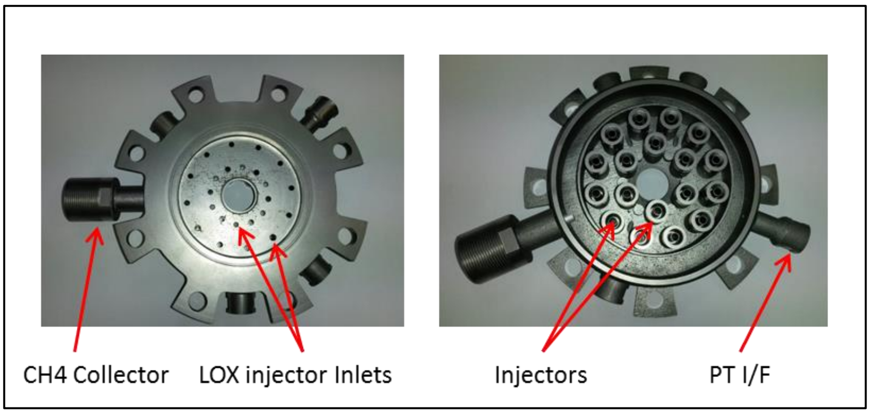

Figure 2: CH4 Dome seen from LOX Dome and firing plate sides (respectively at left and right side of the figure)

As we can see from the previous figures description, all the brazing joints have been eliminated and no weld parts still exist. The 18 injectors have been produced in a single job fusion together with the methane dome. This assured no leak between fuel and oxidizer volumes as well as no more weak points due to special process junctions.
The number of parts has been drastically reduced. Actually, another ALM based element introduced in the assembly was the igniter. Also this product has been manufactured in ALM and a sketch is shown in the next figure.

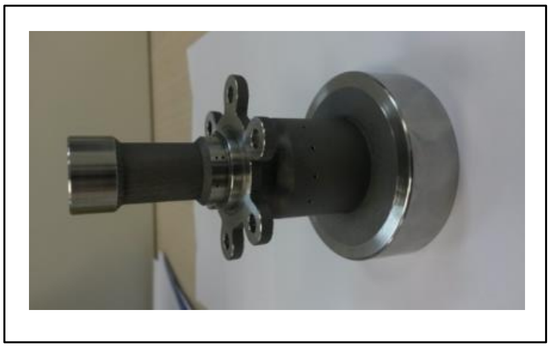

Figure 3: Igniter made in ALM

3.2 Implementation of New Solutions for Innovative Injector Head

The designing logic implemented for this product strived for a better exploitation of ALM benefits with respect to previous injector head. For this reason a new concept was set in order to build an injector head as a single element

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based on ALM manufacturing in addition to the firing plate build up through traditional technology process. In this way, all the issues related to the interfaces and integrations activities have been eliminated and the production process required very few time since the product was realized just in only ALM fusion job.

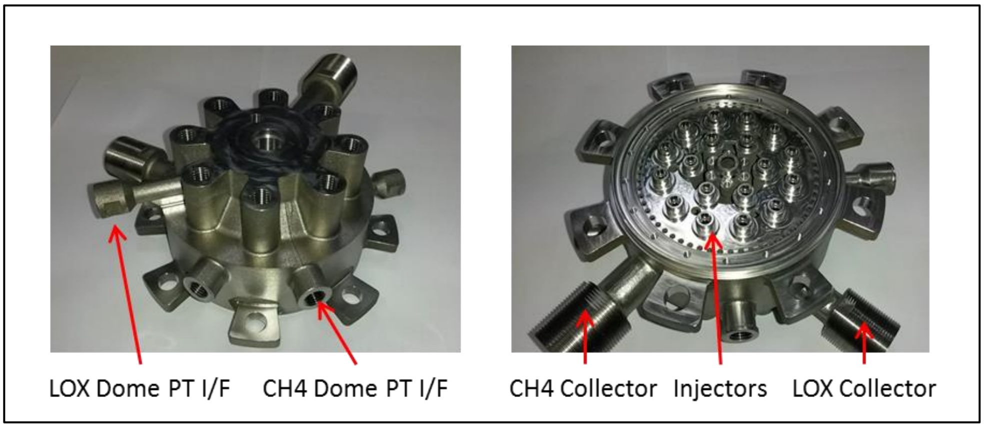

Figure 4: Injector Head seen from top and bottom side (respectively at left and right side of the figure)

Differently with respect to previous injector head, in this case also the igniter is already integrated into the only ALM fusion process. Figure 5 highlights the element detail.

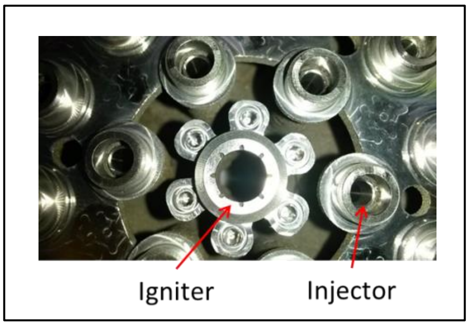

Figure 5: The Igniter already integrated in the main body

3.3 Injector Heads under Development

Exploiting the know-how acquired, AVIO is currently developing 2 new injector heads based on ALM.
The first is characterized by 18 injectors (as the previous products) and the second is composed by 168 injector elements representing a typical class of full scale upper stage injector head. Both the items foreseen the injectors already integrated in the main body during the ALM job fusion.
The 2 products collect all the improvements acquired and are designed as a fit-for purpose hardware.
Furthermore, they represent unique items since a new concept of injector has been implemented by taking advantage of geometry freedom. Moreover, Concept Laser machine (based on laser cusing technique) will be used to realize the objects. The right side of Figure 6 shows the injector envelope used to characterize the element by cold flow tests.
The 2 injector heads are shown in the next 2 figures where the main body (with the injectors included) in Inconel can be observed. From the subscale design is very evident the fit-for purpose hardware designing: the LOX dome has been dimensioned as a “lobos” shape in order to guarantee both the structural resistance and correct igniter interfacing. This particular part has been obtained without any post-processing activities, that, instead, would be needed by Injector Head traditional technology manufacturing. So, a saving of mass, time and costs due to post-processing activities has been reached. The same savings will occur with the full scale product where the main body realization concept will be kept.

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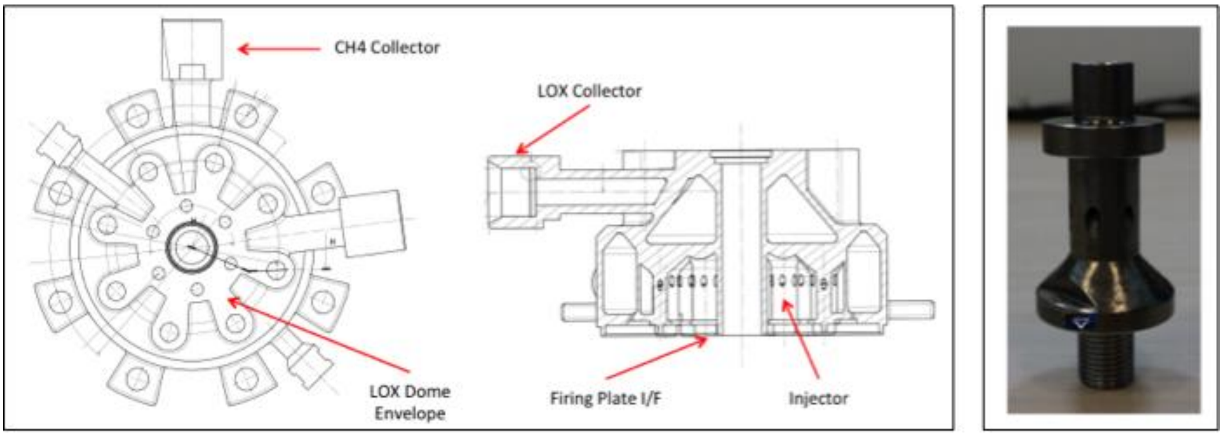

Figure 6: Subscale injector head based on ALM

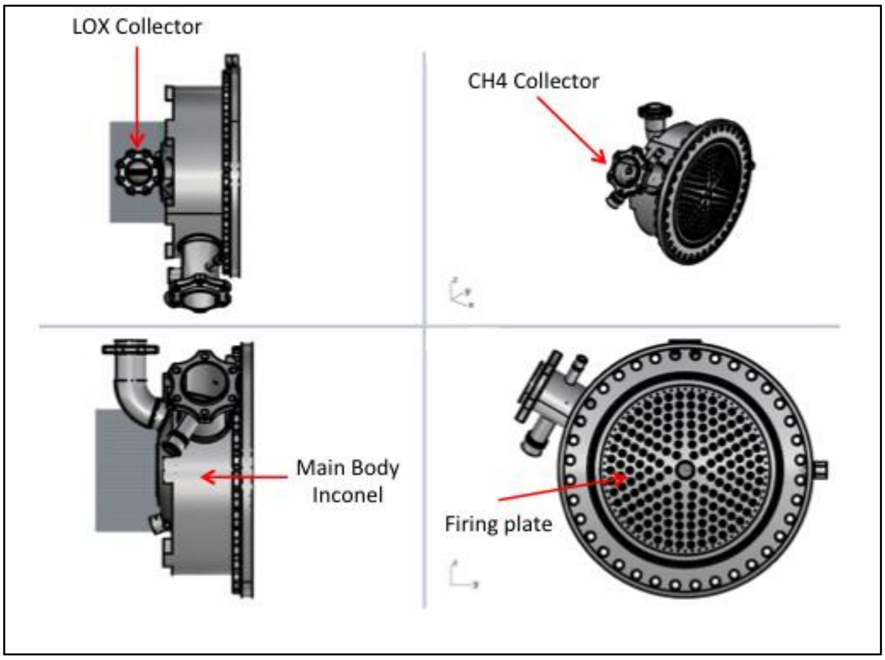

Figure 7: Full scale injector head based on ALM

4. Technological Aspects: how ALM drawbacks are managed

In this paragraph, all the solutions implemented to overcome the drawbacks of ALM process, met during the injector heads manufacturing described before, will be explained.

Roughness of surfaces

First of all, one the main limit is due to roughness of surfaces that is much more higher (7-10 [Ra]) than that achieved by traditional technological implementation. This property affects negatively both the fluid pressure losses, especially for high kinetic energy value, and the capability of reliable interfacing with other parts. So, a strong effort has been spent to solve these two issues by exploiting the ALM capabilities. The first one involved the redesigning of cooling system and injector internal shape, which are the parts where high kinetic content is reached by the fluid during engine working. Suitable geometries have been adopted such as well-rounded corners or smoothed variable cross section instead of sudden ones. In this way, the increasing of pressure losses due to roughness has been compensate by means of decreasing of concentrated pressure losses. The increasing of geometry complexity has been reached for free thanks to ALM shaping freedom property. The second issue related to interfacing capability has been overcome by post-processing activities able to machine the surface to get the roughness accuracy required.

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Overhang angle

Another important issue related to ALM limit is the impossibility to create walls that could have an overhang angle higher than 45° with respect to the productive direction. In this case, metal supports would be needed to build up the parts. These supports are not suitable for internal volume walls due to "main body" production concept. In fact, they could not be removable anyway. The solution implemented to overcome this limit has been to redesign the Injector Heads in such a way the internal walls of the main body could not have overhang angle higher than 45°. This aspect is clearly observable by Figure 6, where an internal injector head cross section is also shown.

Residual stresses

For what concern the residual stresses induced by the fusion process into the material, heat treatments have been implemented to remove them. In particular, for Inconel718 annealing and ageing processes are already foreseen to set the correct mechanical properties. In this way no more residual stresses were keeping in the structure. Furthermore, as a drawback due to ALM process, no information regarding the mechanical properties of the part built up was present. So, material characterization activities have been performed per each job fusion to get the properties required and assure that the requirement of ASTM was met. Here below the main mechanical properties of Inconel718 obtained using both ALM process before and after heat treatments are shown.

Table 2: Comparison between Inconel718 mechanical properties

	AMST Standard [6]	**PBF**			**Comparison**
	+ Annealing + Ageing	**Raw After PBF**	**+ Annealing**	**+ Annealing + Ageing**	**+ Annealing + Ageing**
σ_y [MPa]	≥ 1123	619.7	734.0	1161.0 ± 37.0	3.4%
σ_u [MPa]	≥ 1348	970.3	1063.0	1423.0 ± 21.0	5.6%
E [GPa]	188÷193	139.0	NA	182.0 ± 11.0	-3.2%
ε [%]	≥ 8.0	29.5	32.5	17.0 ± 4.5	112.5%

As we can see from the table above, the ALM properties obtained are slightly higher than those required by the international standard, except for the Young Modulus where ALM shows lower value. This issue is not critical. Rather, for a critical component as injector head is, by working at very high temperature gradients, a little bit lower value of Young Modulus allows to decrease the thermo-structural stresses induced on the structure.
The data refer to a statistical results performed on strength test samples for a fusion job of reference.

Porosity level

The porosity that characterizes a typical Inconel718 part realized in ALM is another issue managed by AVIO. The first evidence was detected on the samples and on the very first injector head manufactured where the porosity affected negatively the product with the creation of a passing hole between the internal and the external part of LOX Dome. In that case, the problem was solved by welding the hole with the main body structure. In Figure 8 it is possible to observe the results of micrography investigation performed on three ALM Inconel718 samples. In Figure 8 the geometry of sample used is shown (right side of figure, where the red rectangles represent just a reference to better detect the locations of worst porosity), as well as the table reporting the dimensions and the positions of the porosity holes (black rectangles).
As we can see from the table above, a very high value of porosity was reached especially for the product after the

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	Worst Porosity	
	Size [µm]	Location
ALM job fusion	40	
Annealing	123	
Annealing + Ageing	148	

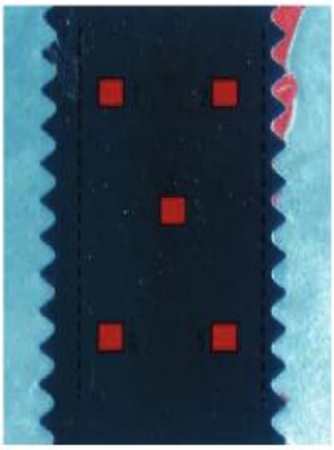

Figure 8: Porosity levels in ALM samples

heat treatments, confirming the affected result obtained on the injector head. To overcome this limit, AVIO implemented a post processing process: the hot isostatic pressing test. Thanks to this process, it has been possible to reduce the porosity, avoiding any passing holes between external and internal part of such a wall.

5. Performance Results

An intense activity has been conducted to tests all the ALM products described in the previous paragraphs. All the experimental campaign have been completed with success, showing the effectiveness of ALM implementation. No substantial difference in performances behavior has been detected.
Cold flow tests have been performed on all of the items as well as a series of firing tests.
In particular, cold flow tests have been carried out on injectors made in ALM. To detect the difference between the performances reached by means of new technology the following tests have been conducted:

- cold flow test on injector (made in ALM) with the same geometry of injectors previously used and made by traditional technology;
- cold flow test on injector (made in ALM) with the same geometry of injectors previously used and made by traditional technology, but with the machined recess;
- cold flow test on new injector (made in ALM) with a reshaped geometry with respect to injectors previously used and made by traditional technology;
- cold flow test on new injector (made in ALM) with a reshaped geometry with respect to injectors previously used and made by traditional technology, but with the machined recess.

The figure below shows one of the test performed on the injector. To simulate the flow conditions, nitrogen and water have been used.

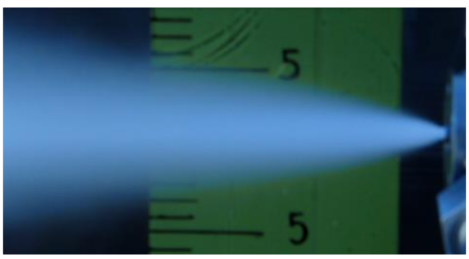

Figure 9: Coupled Nitrogen/Water injector cold flow test

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The main results of this testing activity is reported in the next table that shows the percentage difference between the effective area obtained with ALM and traditionally made injectors.

Table 3: Comparison between effective areas of ALM injectors tested and those of traditionally made injectors

Old Shaped Injector		**New Shaped Injector**	
Not Machined Recess	**Machined Recess**	**Not Machined Recess**	**Machined Recess**
-20%	-13%	-4%	~ 0%

As we can see from the table above, by introducing ALM the pressure losses are affected negatively due to the increased surfaces roughness. The effective areas are decreased between 13% and 20%. The implementation of reshaped internal geometry, instead, influenced positively the results. A proper internal geometry was designed in order to compensate the increasing in pressure losses due to higher roughness with the decreasing of concentrated pressure losses.

Furthermore, hot firing tests have been conducted on the injector heads with CH4 and liquid oxygen. Several tests have been performed with success reaching the maximum chamber pressure foreseen equal to 55 [bar] and a mixture ratio of 3.4. The figure below shows one of the successful firing test performed.

Figure 10: Hot firing test of ALM injector head

The experimental tests showed that performances were no affected by the new implemented technology. The combustion process was conducted without any failure and respecting the results predicted, qualifying the ALM technology as a process that has to be more investigated and exploited to better implement new possible solutions thank to its innovative technological content.

6. Conclusions

The ALM process has been successfully implemented in AVIO Injector Head manufacturing technology. By exploiting all the benefits of the process, some of the limits that always have been met by rocket engine designing have been overcome. Among these, the capability to reshape the geometry of internal walls, the capability to build up the core of the injector head as one single body eliminating all the issues related to the weld, brazing parts, assuring no leak can occur. Moreover, the number of interfaces has been drastically reduced, guaranteeing a much reliable assembly. Some of the ALM drawbacks met during Injector Head designing and manufacturing have been faced and the solutions to overcome them have been implemented. So, the pressure losses have been decreased thanks to proper geometry freedom, a suitable material characterization has been performed to detect the material properties of the Inconel and hot isostatic pressing test has been conducted to reduce the porosity levels. The ALM processes have been performed first by Renishaw machine and then by Concept Laser machine, in order to obtain more accurate finished parts. Several cold and hot firing tests have been successfully completed confirming the feasibility of ALM technology implementation. In general, the gains due to ALM implementation are listed below:

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- reduction of mass: 50 [%] about of traditional injector head prototype;
- lower external envelope: 80 [%] about of traditional injector head prototype;
- reduction of recurring costs: 70 [%] about of traditional injector head prototype;
- increasing of engine reliability since the components are no more related to integration processes.

All these aspects are pushing AVIO to continue in investigating better solutions to exploits at maximum the ALM benefits, involving all the progresses which the worldwide technology is still introducing. Currently, two new injector heads are under development and they collect all the improvements detected up to now.

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