THE ALM APPLIED TO A ROCKET ENGINE INJECTION HEAD – DEVELOPMENT PLAN AND MATERIAL CHARACTERIZATION

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ABSTRACT

Recently, the worldwide rocket propulsion attention has been focusing on innovative manufacturing technologies alternative to the traditional subtractive ones, due to the intrinsic difficulties concerning the welding and brazing of numerous components. The Electron Beam Melting (EBM) is one of the most challenging additive manufacturing technique, since it works with metallic powders at high temperature and in vacuum conditions, so guaranteeing reduced residual stresses and impurities in the final product. CIRA has been equipped with an ALM laboratory made-up of an EBM ARCAM A2x machine and all the auxiliary systems useful to manufacture complex components using the titanium alloy.

The single injector thrust chamber breadboard, named "Subscale Breadboard Heat Sink" (SSBB-HS), already developed and fire tested, has been chosen as the reference breadboard to assess the manufacturing technology effectiveness. The SSBB-HS injection head back plate, originally made in Inconel 718, is re-designed to be manufactured as a unique part by using the EBM technology with the Ti-6Al-4V alloy. The current design of the back plate assembly foresees a main body with manifolds to be welded, and the single injector to be brazed, thus the possibility to make all the parts in a single "machine" run, as a unique part, allows gaining benefits in terms of weight and cost reductions. Once manufactured, the ALM SSBB-HS injection head will be first tested against leakage and pressure proof for the acceptance, and then integrated with the SSBB-HS thrust chamber for a firing test campaign.

In this paper, activities concerning a preliminary thermo-structural analysis of the back plate in Ti-6Al-4V alloy and its re-design tailored on the ALM manufacturing process are presented together with a preliminary test campaign aimed at characterizing the microstructure and the mechanical behaviour of the Ti-6Al-4V alloy processed by EBM. The preliminary mechanical test campaign has been aimed at evaluating the influence of "layer thickness", "skin-microstructure", and "temperature" on modules of elasticity, yield and ultimate strengths and elongations. Outcomes highlight the feasibility of using the Ti-6Al-4V instead of the Inconel 718 alloy, keeping almost unchanged the component mechanical performance, and at the same time by achieving a strong benefit in terms of weight saving. Some warnings regarding the manufacturing process arising from the re-design activity are analysed and properly addressed.

1.0 SCENARIO AND MOTIVATION

Additive Layer Manufacturing (ALM) is an emerging technology by which functional solid parts are made directly from electronic data, generally files from computer-aided design (CAD) software, starting from metal powder. It is based on "layer-by-layer" fabrications and offers many advantages such as short lead time, complex geometry capability, tooling free and very low waste material [1].

Aerospace firms are increasingly turning to the additive manufacturing technology to reduce the costs of developing models and prototypes and of creating components. In a constant effort to reduce aircraft weight, the industry is developing a growing proportion of its parts from titanium, plastic, and other lightweight materials. Many of these materials are costly, and additive manufacturing can make it possible to keep the amount used to a minimum. Aircraft landing gear, for example, can be additively manufactured layer by layer, rather than cut from a raw material block, thereby greatly reducing material waste and costs [2]. Some aerospace applications are jet nozzles, hot structural components up to 500°C. Light Alloys like titanium alloys are mainly employed for space application where thanks to the absence of oxygen the mechanical performances at elevated temperature are exploited. The increasing breadth and sophistication of these applications are, in turn, driving needs for improvements in process control, materials, and inspection to ensure quality and safety ([3], [4]). Despite these advances, limits on the size of goods produced by additive manufacturing together with issues concerning materials, accuracy, surface finish, and certification standards have limited its use.

Recently, the worldwide attention in the aerospace field has been focusing on innovative manufacturing technologies, such as the ALM, alternative to the traditional subtractive ones. Especially in the rocket propulsion field, where the intrinsic difficulties, concerning the welding and brazing of numerous components, are crucial issues to be addressed. The NASA Glenn Research Centre is applying state of the art characterization techniques to interrogate microstructure and mechanical properties of additively manufactured materials and components at various steps in their processing [5]. The materials investigated for upper stage rocket engines include titanium, copper, and nickel alloys. Additive manufacturing processes include laser and electron beam powder bed, and electron beam wire fed processes. Various post build thermal treatments, including Hot Isostatic Pressure (HIP), have been studied to understand their influence on microstructure, mechanical properties, and build density. In Particular, An in-depth characterization of Electron Beam Melted (EBM) Ti-6Al-4V material has been completed. The mechanical properties of HIP'ed EBM Ti-6Al-4V turned out to be equivalent or superior to conventionally manufactured material, probably due to the refined, lamellar microstructure. Inclusions, both low and high density, were present in the EBM Ti-6Al-4V but generally did not affect the mechanical properties of the alloy.

Airbus Defence and Space pursues a comprehensive approach to apply additive manufacturing to liquid rocket engine injectors [6]. The research and technology activities, performed within the National technology program TARES, sponsored by the German Space Agency, and DLR Bonn, address the entire manufacturing process, from material properties and design concepts to non-destructive inspection technologies to allow for the adequate quality assurance by means of a stepwise approach.

The ALM also 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. Today, channels are typically milled and closed with electrical deposition, or alternatively welded or brazed from tubes. In the frame of the DLR-study LAMP (Laser Additive Manufacturing for Propulsion) at the DLR Institute of Space Propulsion, the applicability of ALM Powder-bed Selective Laser Melting (SLM) for production of rocket propulsion components was investigated [7]. The influence of hot firing testing on the P8 test bench at DLR-Lampoldshausen 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.

As concerns CIRA activities, the aim of the materials and processes research line in the HYPROB program is to assess the feasibility and the effectiveness of Additive Manufacturing techniques applied to rocket engine parts already developed in the framework of the same program. The main goal of the program is to design, manufacture and test a liquid oxygen-liquid methane regenerative rocket engine demonstrator. To achieve this final objective, a number of intermediate breadboards have been designed and tested to investigate some critical aspects [8]. Among these breadboards, Single-injector LOX/GCH4 Sub-Scale Breadboard Heat Sink (SSBB-HS) has been chosen for assessing the manufacturing capabilities of Additive Layer Manufacturing (ALM) techniques. Details about design and testing of SSBB-HS are given in [9].

The components to be manufactured by using the EBM technology are: the injectors post, and the Injection Head (IH) back-plate assembly (part #1 in Figure 1-1).

The injector post shall be preliminary manufactured in order to understand the process features and limits, and necessary post-processing activities. The injector head, to be manufactured in a subsequent phase, is an assembly made of three different parts, including also the injector post. In particular, IH is made of a support, and a GCH4 inlet plus the injector post integrated to the support (see Figure 1-2). The idea is to manufacture the IH by Electron beam manufacturing (EBM) as a unique piece.

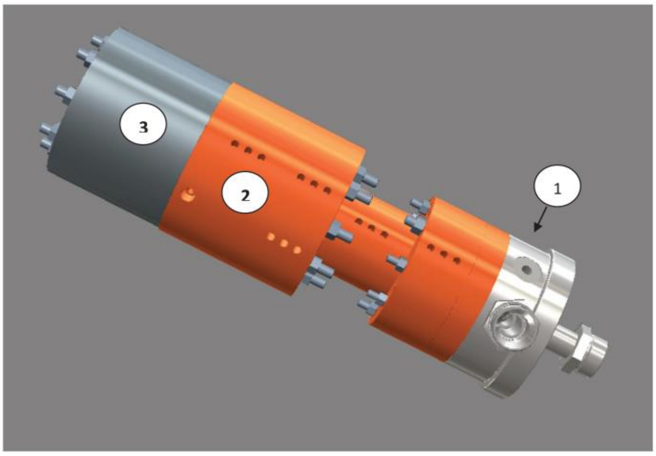


Figure 1-1: View of the SSBB-HS.

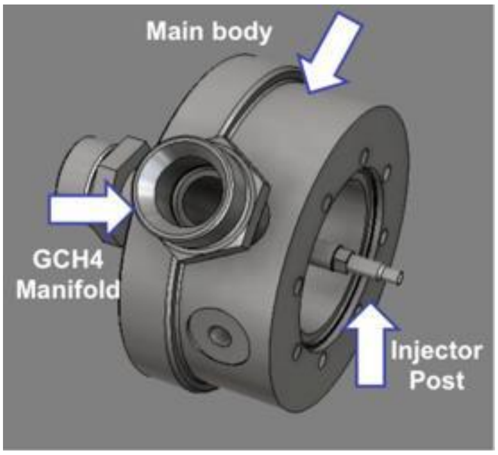


Figure 1-2: SSBB-HS Injection Head Assembly.

Electron beam manufacturing (EBM) is a relatively new ALM technology. A high-energy electron beam, as a moving heat source, locally melts and fuses metal powders and produces parts in a layer-building fashion. EBM is able to make full-density metallic parts, drastically extending AM applications, and significantly accelerating product designs and developments in a wide variety of metallic-part applications, especially for complex components ([10], [11]). One of the main advantages of this technology is the ability to process very hard machinable materials like Titanium, Ti-6Al-4V, Titanium Aluminide, CrCb, Inconel 718 ([12], [13]), materials that have a large spread of application in the aerospace industry, especially in the production of rocket engine parts. Another advantage is the possibility of recycle almost 95% of the unmelted powder leading to a buy-to-fly ratio less than 1.5 for the manufacturing of components. Considering that materials processed with EBM technology are very expensive, the very low buy-to-fly ratio and the very low energy consumption make this technology cost efficient and viable for many industrial application.

On the other hand, despite the potential benefits over conventional manufacturing technologies, EBM still has a few process deficiencies, such as process stability, part defects and quality variations ([14], [15], [16]), etc. Nevertheless, additive manufactured components are typically used in extreme environments and for critical applications in the aerospace industries. As matter of fact, certifying a batch of conventionally produced material is a relatively well-established practice in the manufacturing industry since a lot of specific standard, such as ASTM, ISO or AMS are available. On the other hand, the additive manufacturing industry has not yet adopted a set of test methods or material specifications to standardize the quality control methods to be used in fabricating and certifying layer-based materials [17]. The aim of this study is to characterize EBMed Ti-6Al-4V alloy by performing tensile tests and microstructural analysis on specimens manufactured with different process parameters themes, growing orientation, shape and dimensions. In particular, the influence on mechanical properties of skin-microstructure, layer thickness and temperature conditions have been evaluated. Different sets of tensile specimens have been manufactured: in as-built condition, manufactured directly with their final dog-bone shape, and by machining cylindrical bars. Specimens with different growth orientations (0°, 45°, 90°) with respect to the start plate plane (x-y plane) have been manufactured and tested in order to investigate orientation effects. All the test specimens and test parts are manufactured in the CIRA ALM laboratory, equipped with an ARCAM A2X machine and all the auxiliary systems useful to manufacture complex components using the Ti-6Al-4V titanium alloy.

2.0 SSBB-HSA FEASIBILITY STUDY

In the current SSBB-HS design [9], the Injector Post and the IH assembly are made of Inconel 718. The re-design activity includes the geometry optimization to allow manufacturing the IH as a unique part and exploiting the whole potential of the EBM technology, and the adoption of a lightweight alloy (titanium-based) instead of a nickel-based alloy. In fact, the Ti-6Al-4V alloy is:

- largely used for aerospace applications due to its low density, which allows a **strong weight reduction**, together with its exceptional corrosion and high temperature resistance;
- a standard material for ARCAM machines, with well-known procedures and process parameters;
- better than Inconel 718 in terms of **specific tensile yield and strength** versus temperature in the SSBB operative range (see Figure 2-1);

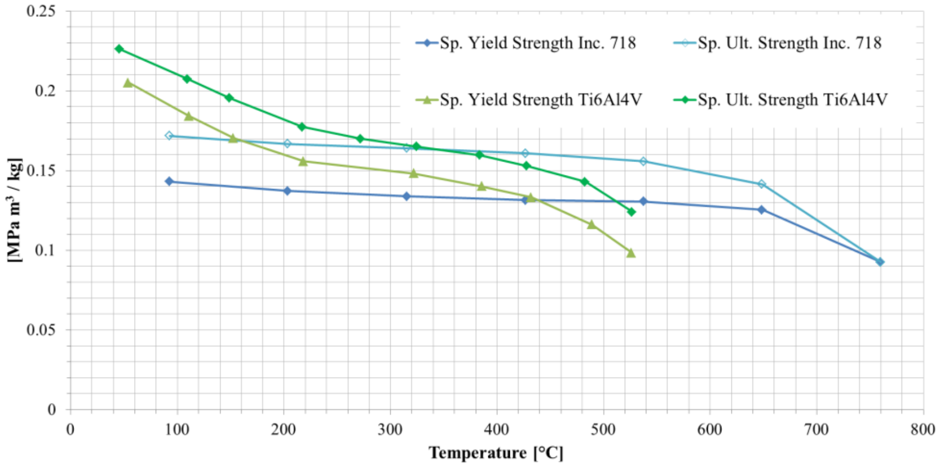


Figure 2-1: Specific ultimate and yield tensile strength versus temperature for Inconel 718 and Ti-6Al-4V alloys.

The opportunity to adopt the Ti-6Al-4V alloy has been evaluated by means of a dedicated feasibility study in order to preliminary verify that neither thermal nor structural criticalities occur during the service life of the Injection Head. Preliminary weight estimations resulted in a weight saving of slightly less than 50% of the original IH weight, for both the adoption of a new material, and geometry optimization. The final bread-board, designed for ALM technology, is code-named SSBB-HSA (SubScale BreadBoard Heat Sink Alm).

Thermo-structural analyses have been conducted by the aid of a commercial finite element code (ANSYS), by using two-dimensional axi-symmetrycal thermal and structural models. Figure 2-2 illustrates a ¾ symmetry expansion of the injector plate FE model. Convective boundary conditions have been applied to simulate the passage of methane and oxygen. Heat fluxes coming from the combustion have been applied to the surfaces shown in Figure 2-2. A static non-linear structural analysis has been performed to study the effects of the thermal expansion during the hot phase. In particular a 6 seconds firing test has been simulated by imposing an adiabatic flame temperature of 3300 K and an internal pressure of 60.5 bar (maximum pressure of the operative box). A Yield Factor of safety of 1.1 and an Ultimate Factor of safety of 1.25 have been adopted. Figure 2-3 shows the temperature contour plot of the injector Head (left). In particular, the temperature distribution in the Ti-6Al-4V back structure is illustrated (right). The maximum temperature value is 122 K. Figure 2-4 shows the margins of safety for the Ti-6Al-4V structure. The minimum value is 2.24, hence the titanium structure results safe against the simulated firing test thermo-mechanical environment. No plastic strains are detected considering the Ti-6Al-4V as an isotropic material.

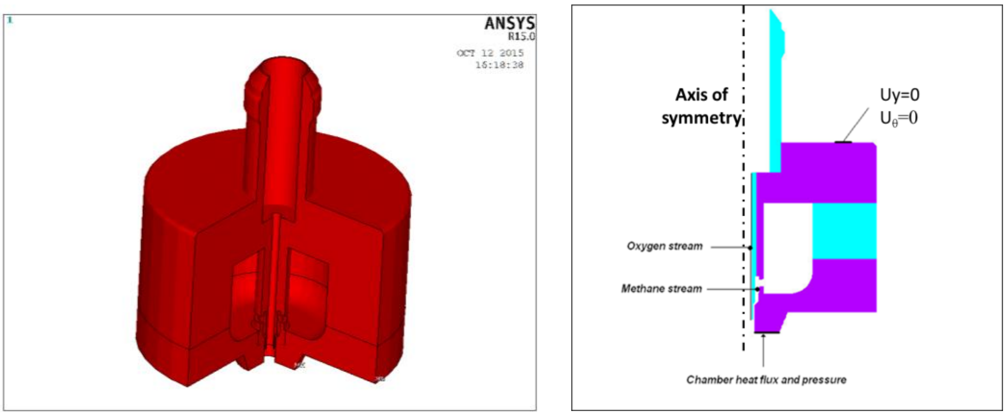


Figure 2-2: 3/4 symmetry expansion of the FE model adopted, Thermal and mechanical boundary conditions.

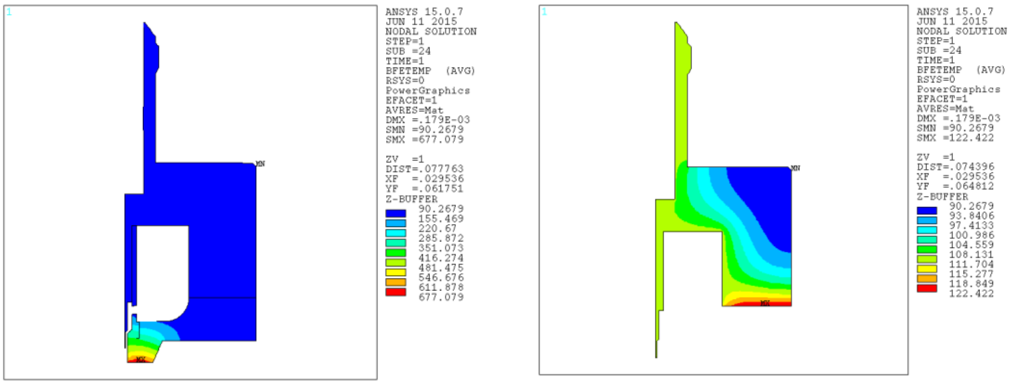


Figure 2-3: Temperature contour plot - hot phase – in the IH, detail in the Ti-6Al-4V back structure.

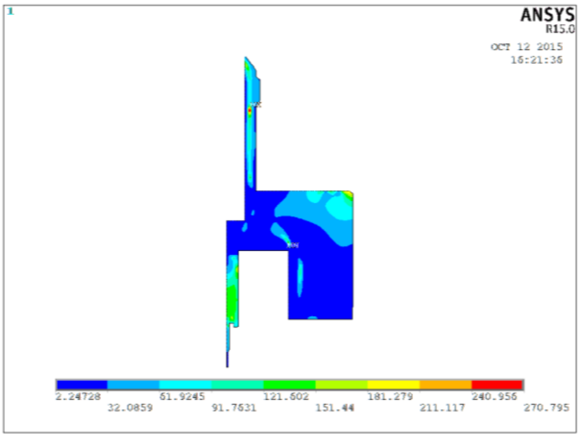


Figure 2-4: Margin of safety – Ti-6Al-4V structure.

The preliminary analysis results in the possibility to use the Ti-6Al-4V alloy, thus to design and manufacture a **lighter** and cheaper Injection Head, with a set of warnings and recommendations mainly due to uncertainties arising from the use of a rather new and not yet fully tested technology.

3.0 PROJECT DEVELOPMENT PLAN

In the frame of HYPROB Program CIRA is developing enabling technologies potentially useful in the design and production of liquid rocket engines. The “materials and processes” research line is dedicated to additive manufacturing technologies for components made of special lightweight metallic alloys, in order to make new rocket engine parts lighter and cheaper. In this frame, after a first trade-off study, the Electron Beam Melting (EBM) technology was selected as the most promising technique.

The overall development of this activity has been split in three main phases (see Figure 3-1):

- **First phase**: trade-off study; procurement of the selected EBM machine, and preliminary training;
- **Second phase**: production of Ti-6Al-4V samples, and mechanical testing. This phase will end with the production of No. 5 to 8 injector post mock-ups for assessing process features and limits, and identifying necessary post-processing activities;
- **Third phase**: production tests and final manufacturing of No. 5 to 8 Injection Head assemblies. The first three to five items are produced to test the better manufacturing process parameters, building angles, and surface post-processes, whereas the last three items are dedicated to the tests.

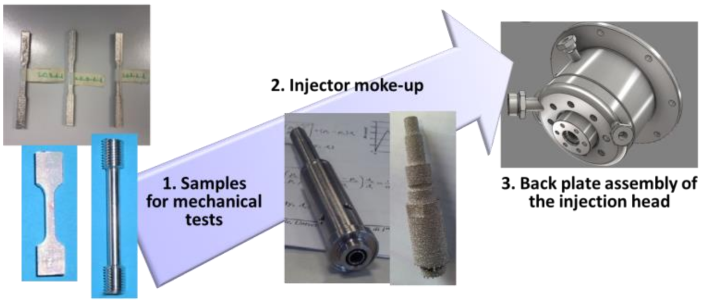


Figure 3-1: Research line development phases.

The **first phase** and **part of the second phase** including static mechanical characterization and first production tests, already completed, are aimed at completing the Technology Acceptance Milestone, that is the acceptance of the EBM technology to produce rocket engine components made of a standard (Ti-6Al-4V) metallic alloy. During the **second phase**, several Ti-6Al-4V coupons are manufactured and mechanically tested at different environment conditions. A fully comprehensive test campaign is planned (and partially completed), involving: Tensile tests at ambient conditions to understand the material behaviour against shape features (circular and rectangular tensile specimens), dimensions, process parameters and building angle; Tensile tests at cryogenic and high temperatures; Fatigue loading tests.

The test specimen number are chosen and the strength and yield allowable are evaluated by taking into account statistical issues. NDI inspections have been performing on all tested specimens in order to correlate the yield and strength levels with possible manufacturing defects. During the same phase, an Injector Post mock-up are manufactured for preliminarily assessing and optimizing the manufacturing process quality, to characterize the manufacturing response to dimensional, tolerance and roughness requirements. Indeed, for both test samples and injector mock-ups, a study of building configuration angles is necessary. Different specific post-processes have been studying and testing in order to obtain the required roughness and tolerance levels. Geometrical analysis are also running in order to check the compliance of the injector mock-up to the requirements of geometrical tolerance and surface features.

Following the same conceptual steps of the injector mock-up manufacturing, in the **third phase** a more complex engine component will be produced in Ti-6Al-4V alloy; the goal is to build the re-designed IH back plate assembly of the SSBB-HSA demonstrator. The purpose is to compare the items manufactured by EBM with the original one already produced by means of standard manufacturing process. After a preliminary activity concerning dimensional analysis, roughness analysis and NDI inspections (liquid penetrants and X-ray in order to detect major defects), the following tests will be performed:

- A proof test of the oxygen line and the methane line with a pressure of 2*MEOP (Max Engine Operating Pressure), with the repetition of the NDI inspections after the test;
- A leak test at 2*MEOP of the back body integrated with the copper plate (see Figure 3-1);
- A strong proof test at a pressure of 3*MEOP of the back body integrated with the copper plate;
- A leak test at MEOP of the whole assembly;
- A firing testing activity with a test matrix to be defined according to the technological and redesign activities results.

Leak, Proof and Firing tests are planned to be carried-out in the CIRA facility HYPROB IMP, currently under development. The final target is to reach a TRL level between 4 and 5.

The whole research line requires a manpower effort estimated in about 9000 working hours including design, manufacturing and test engineering specialists, with less than 100 k€ of direct costs, including software, hardware, raw materials, expendables, and testing facility costs. The above direct costs do not account for the initial investment for the supply and setup of the ALM machine and the related ancillary equipment.

4.0 MATERIAL CHARACTERIZATION

In this section micro-structural analysis and mechanical testing activities, finalized to the thermo-mechanical characterization of titanium parts manufactured by EBM, are presented.

Several Ti-6Al-4V coupons have been manufactured and tested at different environment conditions. The experimental campaign involves the following tests:

- Tensile tests at room temperature to understand the material behaviour vs. skin microstructure;
- Tensile tests at room temperature to understand the material behaviour vs. growing direction;
- Tensile tests at room temperature to understand the material behaviour vs. process parameters;
- Tensile tests at cryogenic and high temperatures.

Considering the good repeatability of the tensile tests results, for each test condition, 3 replications have been performed and the results have been processed by taking into account statistical issues.

4.1 Micro-Structural Analysis

Typically, Ti-6Al-4V samples from EBM show an ordered lamellar microstructure, consisting of extremely fine grains, as can be expected by the thermal characteristics of the EBM process: small melt pool and rapid cooling. EBM components possess α columnar shaped morphology of the prior β phase with a growing direction parallel to the build direction ([18], [19], [20], [21]), which is a consequence of primary thermal gradients that exist in the build direction. Optical microscope analysis have shown a typical (α+β) structure, very fine lamellar α+β microstructure consisting of basket-weave structure. This result have been observed for both sets of samples, 50 μm and 100 μm thickness process themes (Figures 4-1-a and -b).

Figure 4-1-a: Microstructure of 100 µm process theme sample.

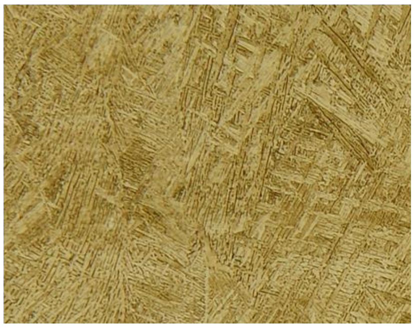


Figure 4-1-b: Microstructure of 50 µm process theme sample.

Micrograph have been shown for 100 µm process theme sample significant microstructural defects in particular lack of fusion between several layers as reported in the figure 4-2, and a porosity homogeneously distributed reported in Figure 4-3.

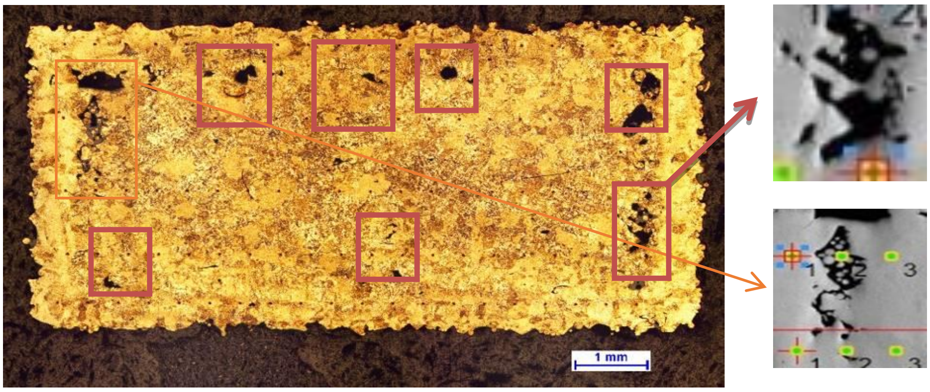


Figure 4-2: Micrograph of 100 µm process theme sample showing significant lack of fusion between layers.

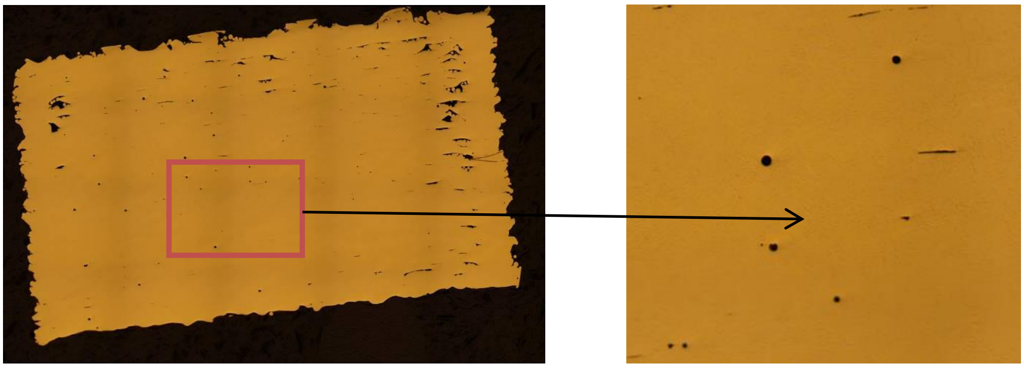


Figure 4-3: Micrograph of 100 µm process theme sample showing porosity.

On 50 µm process theme samples microscope analysis have shown a not severe porosity distribution as shown in Figure 4-4-a, no evidence of lack fusion between layers have been observed, just occasionally a slight fusion inconsistency as reported in Figure 4-4-b.

Figure 4-4-a: Micrograph of 50 µm process theme sample showing porosity.

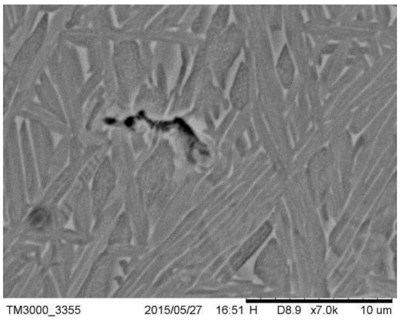


Figure 4-4-b: Detail of a 6 µm lack of fusion.

4.2 Tensile Tests

The tensile tests, compliant to the ASTM E8, have been performed on EBM built Ti-6Al-4V tensile samples ([16], [22], [23]).

With the aim of investigating the **effect of the "skin-microstructure**" on the mechanical properties, tensile tests on EBMed specimens in as built condition and on machined ones have been performed. The two sets of tensile specimens have been EBM manufactured by using the same process parameters: layer thickness and the relative process parameter theme of 50µm. The test samples have been manufactured with a standard round cross-section, with different growth orientations (0°, 45°, 90°) with respect to the start plate plane (x-y plane) for both sets of tensile samples: as built and machined.

Moreover, the tensile specimens have been manufactured also with different process parameters themes in order to investigate the **influence of the slicing parameter**, i.e. the layer thickness used during the "layer-by-layer" fabrication, on the tensile behaviour of the material. Two sets of sub-size rectangular specimens, manufactured by using the layer thickness of 50 µm and 100 µm respectively, have been tested under tensile condition. Orientation effects have been investigated too: for both sets, specimens with different grow orientations (0°, 45°, 90°) with respect to the start plate plane (x-y plane) have been manufactured and tested.

Finally, with the aim of investigating the **effect of the temperature** on the mechanical properties, tensile tests on EBMed specimens at 190°C and -150°C have been performed. Even in this case the specimens were manufactured with different growth orientations (0°, 45°, 90°) with respect to the start plate plane (x-y plane) and with a small size round cross section.

The whole test campaign involve a total of No. 20 tensile tests of rectangular cross-section specimens and No. 39 tensile tests of circular cross-section specimens of various dimensions. In the following tables, 7 different specimen categories are named as follows:

1. SUBSIZE_RECTANGULAR_50_AS BUILT
2. SUBSIZE_RECTANGULAR_100_AS BUILT
3. STANDARD_ROUND_50_AS BUILT
4. STANDARD_ROUND_50_MACHINED
5. SMALL SIZE_ROUND_50_AS BUILT
6. SMALL SIZE_ROUND_50_AS BUILT_190°C
7. SMALL SIZE_ROUND_50_AS BUILT_-150°C

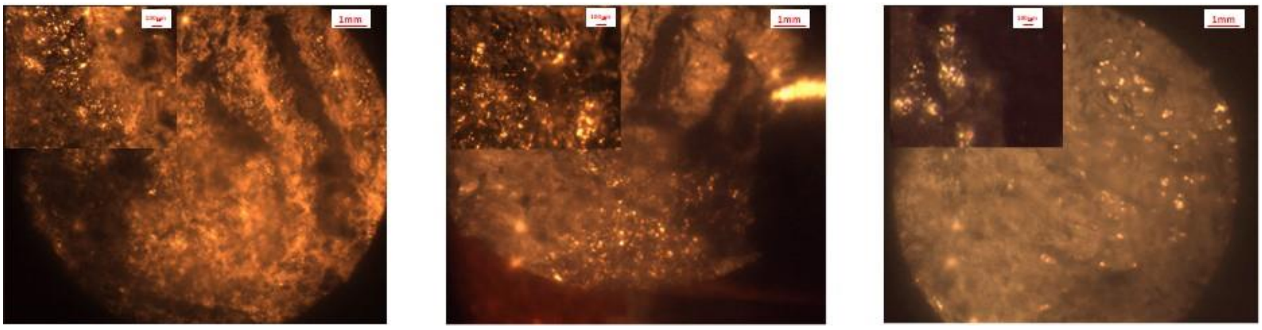
Tensile tests of categories 3 and 4 (having standard dimensions according to ASTM E8) have been performed on the servo-hydraulic testing machine for static and dynamic tests MTS 810 with cell load capacity of 250kN. Conversely, tensile tests of categories 1, 2, 5, 6 and 7 (having reduced dimensions) have been performed on the electromechanical static machine Instron 4505 with cell load capacity of 100kN.

Both the machines used for the tensile tests are equipped with a data acquisition system able to gather all the load and displacement data necessary to implement the (σ- ε) diagram. The elastic modulus, the yield strength, the ultimate strength, and the final strain have been extrapolated from engineering stress-strain curve. The Yield strength is calculated at the stress value of 0.2% plastic deformation ($\sigma_{0.2}$ YS). The Ultimate tensile strength is the engineering stress value or σ_{UTS}, at the maximum of the engineering stress-strain curve. It represents the maximum load, for that original area, that the sample can sustain without undergoing the instability of necking, which will lead inexorably to fracture. The final strain is the engineering strain value at which fracture occurred.

The results of the tensile tests for the standard round specimens are shown in Table 4-1 in terms of Young modulus (E), yield strength (σ_{02}), ultimate strength (σ_{max}) and failure strain (ε_{max}). The growing orientation has been found having no significant influence on the mechanical properties of the material. As matter of fact, each mechanical property (Young modulus, yield and ultimate strength) was found not influenced by the growing direction and small deviation are within the statistical data dispersion. Such small deviations are most likely due to the random presence of colonies of not melted powder particles (Figure 4-5) which at the moment cannot be controlled during the process.

		E [GPa]			σ02 [MPa]			σmax [MPa]			εmax [%]	
		Average	ST.DEV	RELATIVE ST.DEV	**Average**	ST.DEV	RELATIVE ST.DEV	**Average**	ST.DEV	RELATIVE ST.DEV	**Average**	ST.DEV
3. STANDARD_ROUND_50_AS BUILT	0°	**98,8**	2,3	2,3%	**853**	10,0	1,2%	**915**	9,3	1,0%	**7,6%**	1,0%
	45°	**107,9**	0,4	0,3%	**859**	26,9	3,1%	**918**	24,9	2,7%	**11,3%**	2,7%
	90°	**104,8**	1,5	1,5%	**857**	8,6	1,0%	**919**	8,5	0,9%	**7,4%**	2,1%

Table 4-1: Test results



a) b) c)

Figure 4-5: Micrograph showing colonies of non melted powder for specimens grown at 0° (a), 45° (b) and 90°(c)

The experimental test campaign allowed investigating the influence of the following parameters/conditions on the mechanical behaviour of the material:

- **Skin microstructure** (STANDARD_ROUND_50_AS BUILT vs. STANDARD_ROUND_50_MACHINED)
- **Thickness layer** (SUBSIZE_RECTANGULAR_50_AS BUILT vs. SUBSIZE_RECTANGULAR_100_AS BUILT)
- **Temperature** (SMALL SIZE_ROUND_50_AS BUILT vs. SMALL SIZE_ROUND_50_AS

BUILT_190°C vs. SMALL SIZE ROUND_50_AS BUILT_-150°C)

In Table 4-2, a comparison of tensile tests results is presented. In particular, the influence of the following parameters/conditions on the mechanical behaviour of the material have been evaluated against a baseline:

- Surface finish condition (STANDARD_ROUND_50_AS BUILT vs. STANDARD_ROUND_50_MACHINED)
- Thickness layer (SUBSIZE_RECTANGULAR_50_AS BUILT vs. SUBSIZE_RECTANGULAR_100_AS BUILT)
- Temperature (SMALL SIZE_ROUND_50_AS BUILT vs. SMALL SIZE_ROUND_50_AS BUILT_190°C vs. SMALL SIZE ROUND_50_AS BUILT_-150°C)

		effect of the "skin-microstructure"				influence of the slicing parameter				influence of the temperature			
		E [GPa]	σ02 [MPa]	σmax [MPa]	εmax [%]	E [GPa]	σ02 [MPa]	σmax [MPa]	εmax [%]	E [GPa]	σ02 [MPa]	σmax [MPa]	εmax [%]
1. SUBSIZE_RECTANGULAR_50_AS BUILT	0°					BASELINE							
	45°												
	90°												
2. SUBSIZE_RECTANGULAR_100_AS BUILT	0°					6,40%	-3,17%	0,57%	1,57%				
	45°					1,34%	-1,08%	-4,25%	-6,27%				
	90°					-4,17%	-3,33%	-4,86%	-3,67%				
3. STANDARD_ROUND_50_AS BUILT	0°	BASELINE											
	45°												
	90°												
4. STANDARD_ROUND_50_MACHINED	0°	18,97%	10,25%	7,77%	-4,91%								
	45°	6,36%	6,32%	6,08%	-4,38%								
	90°	9,98%	11,75%	10,93%	6,4%								
5. SMALL SIZE_ROUND_50_AS BUILT	0°									BASELINE			
	45°												
	90°												
6. SMALL SIZE_ROUND_50_AS BUILT_190°C	0°									-0,40%	-28,18%	-19,93%	9,44%
	45°									-2,08%	-26,16%	-20,70%	7,27%
	90°									-3,52%	-18,14%	-11,89%	2,00%
7. SMALL SIZE_ROUND_50_AS BUILT_-150°C	0°											19,71%	-3,69%
	45°											21,57%	-3,40%
	90°											22,36%	-11,93%

Table 4-2: Benchmark of tensile tests results

As far as the failure strain is concerned, results show that the fracture behaviour is significantly affected by metallurgical defects as voids and lack of fusion that yield to brittle failure. Since the defects distribution is random, there is no evidence of trend between failure strain and tensile specimen conditions (growth directions, slicing parameters and skin microstructure).

The **skin microstructure** seems to have a significant influence on the mechanical performances (Young Modulus, yield strength and ultimate strength). As matter of fact, the machined specimens show higher performances with respect to "as built" specimens for each growth direction, probably because by machining the specimens, the weakest microstructures of the material, i.e. the skin microstructure, is removed.

The **thickness layer** seems not to significantly affect the mechanical properties of the Ti-6Al-4V electron beam melted as long as the material is processed with the appropriate process theme. Indeed, no great difference can be found by comparing results provided by the specimens manufactured with a thickness layer of 50 µm with those ones manufactured with a thickness layer of 100 µm.

As known, the **temperature** affects the mechanical properties of the Ti-6Al-4V electron beam melted. In particular, at 190° C a decrease of the tensile strength of about 20% has been found. Due to unavailability of a suitable strain measurement device, the Young modulus and the yield strength at cryogenic temperature have been not measured. As expected, a brittle behaviour has been observed at -150°C, where an increment of the tensile strength and a decrease of the failure strain was found. In particular the ultimate tensile strength was found about 20% higher with respect to value found at room temperature.

6.0 CONCLUSIONS

Recently, the worldwide rocket propulsion attention has been focusing on innovative manufacturing technologies alternative to the traditional subtractive ones, due to the intrinsic difficulties concerning the welding and brazing of numerous components. Our aim of assessing the feasibility and the effectiveness of Additive Manufacturing techniques applied to rocket engine parts passed through the evaluation of the Electron Beam Melting (EBM) technology, recognized as that one guaranteeing very low levels of residual stresses and impurities in the final product.

In this paper the technology roadmap and the research line study logic have been presented. The single injector thrust chamber breadboard, named "SubScale BreadBoard Heat Sink" (SSBB-HS), already developed and tested in the framework of the HYPROB program, has been chosen as the reference breadboard. The SSBB-HS injection head back plate, originally made in Inconel 718, is re-designed to be manufactured as a unique part by using the EBM technology with the Ti-6Al-4V alloy. The current design of the back plate assembly foresees a main body with manifolds to be welded, and the single injector to be brazed, thus the possibility to make all the parts in a single "machine" run, as a unique part, allows gaining benefits in terms of weight and cost reductions. Once manufactured, the ALM SSBB-HSA injection head will be first tested against leakage and pressure proof for the acceptance, and then firing tested for technology effectiveness demonstration, as final objective of the project.

In this paper preliminary activities concerning a thermo-structural analysis of the SSBB-IH component in Ti-6Al-4V alloy and its re-design tailored on the ALM manufacturing process are described together with microstructural and thermo-mechanical characterization of Ti-6Al-4V alloy specimens processed by EBM.

The initial test campaign has been finalized to evaluate:

- The influence of the "**layer thickness"**;
- The influence of the "**skin-microstructure**";
- The influence of the "**temperature**".

Results are in a good agreement with the literature, showing that, although the skin microstructure seems to have a significant influence on the mechanical performances, the thickness layer seems not to significantly affect the mechanical properties of the Ti-6Al-4V electron beam melted as long as the material is processed with the appropriate process theme. Finally, as expected, lower strength properties (yield and ultimate strength) and higher failure strain were found by increasing the temperature. On the other hand, higher ultimate strengths and lower failure strain were found by decreasing the temperature. Although it was not possible to measure the Young modulus at cryogenic temperature, it is reasonable to think that such modulus is not significantly influenced by the temperature as demonstrated by comparing the test results at room temperature with those ones at 190 °C.

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