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Metal 3D printing for RF/Microwave high-frequency parts

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1 Background

Satellite platforms provide limited DC power and accommodation, pushing any sub-system to make efficient use of these key resources. The constrains related to these aspects are further stressed when considering small platforms where the available DC power and the platform volume/mass limits are much reduced. Microwave parts for space applications, such as those based on waveguide structures, benefit from an additive manufacturing approach in terms of Radio Frequency (RF) performance and compactness, responding to the general trend to embark payloads in smaller platforms. This benefit has been already proven at traditional microwave frequencies such as C-, Ku- or even Ka-band. Selective Laser Melting (SLM) in Aluminium has been, in most of the cases, selected as the preferred building technology for microwave parts. Though SLM RF parts showed in general good RF performance, aspects such as manufacturing tolerances and roughness are a concern for microwave engineers, getting more critical when moving toward higher frequencies (beyond 30 GHz). Another important aspect to be taken into account is the required time for production and cost that, in the case of SLM, tend to be in the high side. Metal Binder Jetting has been identified as a promising manufacturing technology for RF parts operating at high frequencies. This manufacturing technique does not involve high-energy sources during the layer-by-layer building and does not require support structures, which translates into good surface roughness. In addition, up to x10 cost reduction is claimed with respect to SLM parts when considering low-to-medium size productions. On the other hand, the process requires a high temperature excursion during sintering that induces shrinkage of the part.

Currently, due to the demanding requirements for space parts, metal 3D printing is the preferred option and this is why this review paper will focus on this type of manufacturing leaving outside the discussion regarding the use of 3D printed parts using polymer or ceramic materials. This paper aims to present a short overview of RF equipments, its suitability for the manufacturing using 3D printing, examples of 3D printed RF parts and a discussion regarding pros and cons associated with each process and application.

2 Introduction

The review of the state of the art of 3D printing is commonly addressed from the process point of view, providing examples which can benefit from each process. It is also common to find claims

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regarding the enabling nature of 3D printing when designing and building complex 3D parts. This approach is, somewhat, agnostic in terms of application and helps to generally understand each manufacturing process and its capabilities. However, a complete review following this approach can become cumbersome with the current landscape where a huge number of materials and manufacturing techniques are available.

At this point in time, the general philosophy behind a 3D printing process is well understood by most of the engineers or at least it is very easy to get familiar with its main features. Review papers appear in the literature every year, getting also quickly obsolete due to the fast evolution of manufacturing processes and the availability of new materials. This should not be understood as a negative comment, as each review paper meets an educational purpose and smooths the way for newcomers in the field. Indeed this paper itself is, at some extent, a pedagogical exercise. However, this paper does not aim to provide an exhaustive review of works but to provide some examples in relation with the use of 3D printing for the manufacturing of RF parts. The reader is also referred to some recent review papers on metal 3D printing technologies such as [1], [2] and [3].

Standards are well accepted by the industry and academia as means to guarantee certain quality in the processes and products. This also applies to 3D printed parts where repeatability, accuracy and resulting material properties are key aspects to be granted over the entire print, between prints, and across different printer manufacturers. The development of the standards is well summarised in [2], though it must be also remarked that these standards are not widely adopted by industry resulting in high degree of customisation of the process for each customer. There is also a need for the development of specific standards related to 3D printing for space applications. The European Space Agency has recently issued [4] - ”Processing and quality assurance requirements for metallic powder bed fusion technologies for space applications - ECSS-Q-ST-70-80C Rev. 1”. The priority has been given to this process since it is the preferred one in the space industry at the moment. It is particularly interesting [3] where direct and indirect manufacturing approaches are discussed and introduced as per Fig. 1, though not all of them are used for the manufacturing of metal parts. Indirect manufacturing approaches could bring some advantages in the case of metals since high energy sources are not required, which could contribute to improve parameters such as accuracy or surface roughness.

This paper aims to present a review from the application point of view and, in particular, from the RF/Microwave perspective. Additional requirements/constrains will be also discussed when considering aspects related to the space environment. Some of the most important are described in [5] where the space environment is described as ”a set of environmental conditions created or modified by the presence or operation of the item and its mission (e.g. contamination, secondary radiations and spacecraft charging). The space environment also contains elements which are induced by the execution of other space activities (e.g. debris and contamination)”. The description of the space environment is imposing already very stringent requirements in terms of materials that can be used to build parts. However, these requirements depend on the orbit for the mission and, to a lesser extent, the launch strategy to reach the final orbital position. In [6], an introduction to the main aspects impacting the material selection is briefly provided. Spacecrafts and launchers are exposed to a harsh environment including exposure to extreme temperature gradients, high radiation doses, vacuum, micrometeoroids and space debris hyper velocity impacts, as well as planetary-specific environmental conditions. Fig.2 is also included in [6] and provides a view on some of the most important aspects to be taken into account during the design phase of a space mission. An important take over from the paper is the reference to potential issues related to the degradation of polymeric materials due to solar and cosmic radiation.

For instance, missions operating in Low Earth Orbits (LEO), such Earth Observation satellites or telecommunication constellations will be subjected to high energy particles, atomic oxygen and daily temperature variations. Special cases are those for exploration missions where the environmental conditions must be carefully considered. As a matter of example, the solar intensity

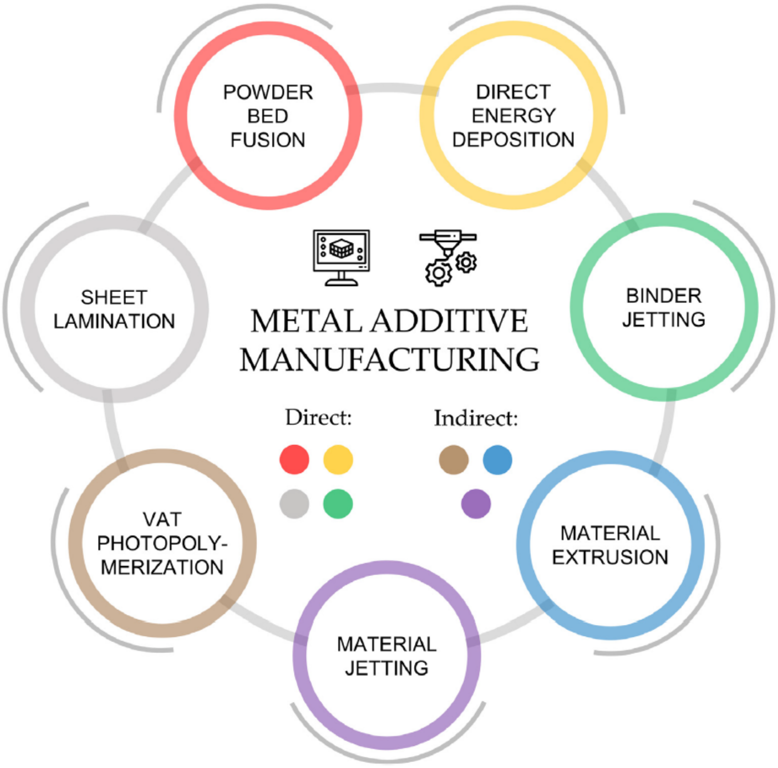

Fig. 1 Classification of additive manufacturing with identification of its direct and indirect suitability to build metal parts [3]

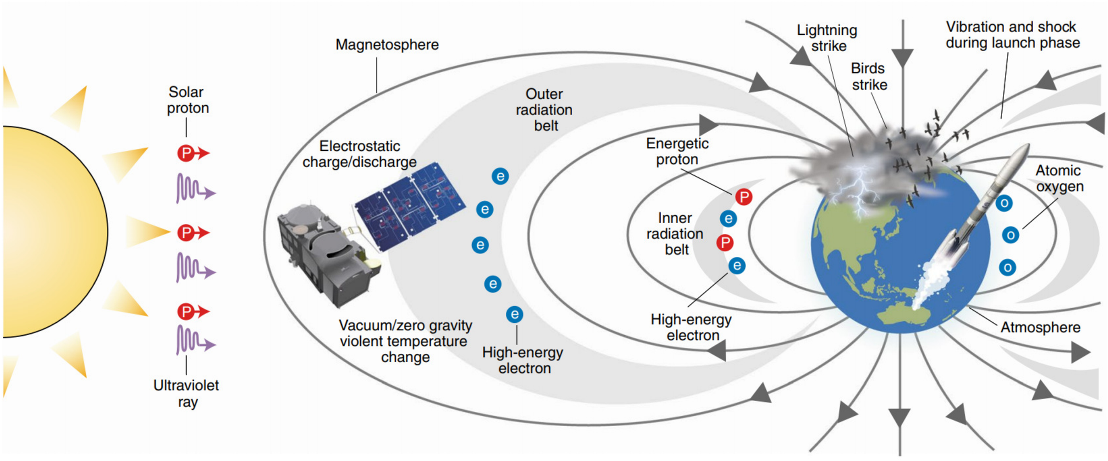

Fig. 2 Challenges for spacecraft materials [6]

at Mercury is about 10 times that at Earth, and the European Space Agency (ESA) mission BepiColombo experiences temperatures in excess of 450˚C. To cope with this, the spacecraft's external items, such as the antennas, solar arrays, Sun sensors and multilayer insulators, have temperature-resistant outer layers and protective coatings, which were individually qualified to prove their capability. Over 80% of the materials had not been tested in such an extreme environment before. To have representative test conditions, the solar simulator at ESA's test centre had to be modified to deliver a flux much higher than that for which it was originally designed. The spacecraft withstands also large changes in temperatures at Mercury – at night it can drop to –180ºC. Fig. 3 summarises the environmental conditions and the design aspects which have been considered to meet the requirements.

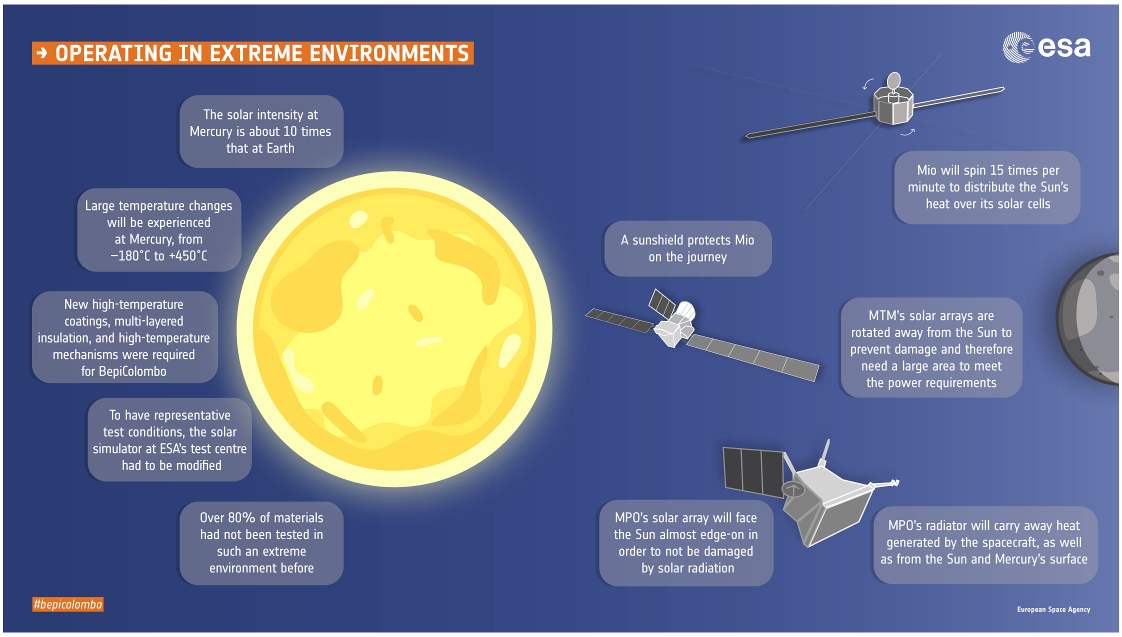

Fig. 3 BepiColombo: operating in extreme environments [7]

The space environment translates to stringent requirements for the materials in order to guarantee a high reliability of the mission. This requires an extensive trade-off for the available choices, resulting sometimes in a narrow down-selection of high performance materials. Guidelines for the selection of materials for space missions are provided in [8] and data regarding specific material can also be found in SPACEMATDB - Space Materials DataBase, which can be easily found in the Internet.

3 Metal RF parts - A short review

The introduction of this paper was already showed that the selection of the material and manufacturing process has to be done considering , in the first place, specific requirement of the mission. This first step is not related to any RF application yet, but will contribute to the down-selection of a reduced number of materials which can be used in space. It deserves to be said that the current landscape for materials is growing fast and there is a vast amount of information regarding the suitability for the space environment which is still missing. Manufacturers for space parts tend historically to be conservative in their design approach and high level of maturity is required in order to have a reduced technology/mission risk. However, the increase in the number of private commercial space missions is also leading to higher degree of competition among manufacturers. This is also bringing new players in the market with more aggressive approaches for the production of space hardware.

Design drivers will be mission dependent and a trade-off for the selection of the best design and manufacturing approaches must be performed. Some of the main parameters to be considered in the trade-off for RF function design and manufacturing are described here:

- **Accommodation**: limitations in terms of available space for the RF part accommodation can be due to the small size of the platform (e.g cubesats, minisats) or the high number of elements to be accommodated in a given platform (e.g. Very High Throughput Satellites).

- **Number of units**: material and manufacturing process selection can also be dependent on the number of units to be manufactured. As a matter of example, injection moulding cannot be considered for the production of small number of units while 3D printing is suitable for low to medium numbers.
- **Losses**: Ohmic losses will directly penalise the RF performance of the overall system but will also impact the overall power efficiency. Considering that DC power is a precious parameter in satellites, high efficiency and low loss RF devices are needed.
- **Thermal and Mechanical**: Thermal aspects are due to the environment itself because of the in-orbit operation and due to the self-heating related to ohmic losses and efficiency of the active stages. The parts have to be able to withstand the mechanical loads due to the launch, deployment or simply in-orbit manoeuvrers.
- **High Power**: RF high power operation will also affect the design choices. Average power handling is the main parameter to be taken into account but other aspects such as multipactor or passive intermodulation products have to be also carefully considered.

RF parts are present in all space missions and also as constituents of the communication systems used in the launchers, working from frequencies of a few hundreds MHz up to hundred of GHz. The frequency of operation is another parameter that will have an impact on the selection of the end-to-end manufacturing process. Since the frequency is inversely proportional to the wavelength, the higher the frequency is, the lower the wavelength. This is one of the reasons why low frequency RF parts are built using, in most of the cases, microstrip/stripline/coaxial technology which provides a high level of miniaturisation at the expenses of a small penalisation on RF losses. On the contrary, at frequencies beyond 20GHz parts are already very small and the accommodation aspects could be not the driver but RF performance. This will result in design strategies to reduce as much as possible the losses.

The space segment is commonly divided into the platform system and payload/instrument system. The platform system hosts the payloads/instruments providing communication, command, data handling, electrical power, propulsion, thermal control, attitude control, guidance and structural accommodation. Most of the satellite integrators have developed standard platforms where some of the subsystems are customised to meet specific mission requests. The most common RF subsystems in the platforms are related to TT&C and data downlinks in case this is required.

An example of a communication subsystem is provided in Fig. 4 from [9]. This specific case is related to the data downlink for the instruments embarked on board the Juice satellite, operating in transmit at two frequency bands: X- and Ka-band. Modules before the Travelling-Wave Tubes (TWT) (or, generally speaking, before the high power amplifier) are highly integrated while the RF front-end (from the TWTs to the antennas) are designed using high performance technologies such as waveguides. Three types of antennas are required for this subsystem: Low, Medium and High gain antennas. Some examples for the antenna implementation are provided in Fig. 5. The examples are directly extracted from the antenna portfolios of RUAG, SENER Aeroespacial, and Thales Alenia Space, which are available in their respective websites. It is important to remark that the Medium Gain Antenna (MGA) is deployed once the spacecraft reaches the orbit, while it is stowed during the launch. From the examples provided in Fig. 4 and Fig. 5, one can start assessing which part could be manufactured using advanced manufacturing techniques such as 3D printing, and which clear advantages are detected. The use of 3D printing to build RF parts must indeed bring specific advantages with respect to the use of traditional manufacturing techniques. The questions to answer are what can be done and what can be improved by using 3D printing as the manufacturing process for our RF part. Let's take as an example the High Gain Antenna (HGA) main reflector presented in Fig.4 and let's consider the mass as the main requirement driving its development, while the RF, thermal and mechanical performance are aimed to be comparable to the ones achieved when manufacturing the part using conventional techniques. The RF performance will impose requirements to the reflector design such as the size, thermo-structural stability and roughness among others. The first question can be already answered: is it possible to manufacture the reflector using 3D printing to meet the size/stability and roughness requirements? If yes, the second question can be also answered: what can be improved? If the improvement is in terms of cost or mass reduction, which are our main drivers, then the manufacturing of this part using 3D printing is well justified. This is, for sure, a path to follow when developing a product but, is this the best approach when considering R&D activities? There is a current trend to unnecessarily increase the complexity of RF designs without any benefit in terms of performance but resulting in complex geometries that can only be manufactured using 3D printing. This is a delusion since the resulting demonstrator will, most probably, be more expensive due to the effort required for the design and qualification of the part and processes among other aspects.

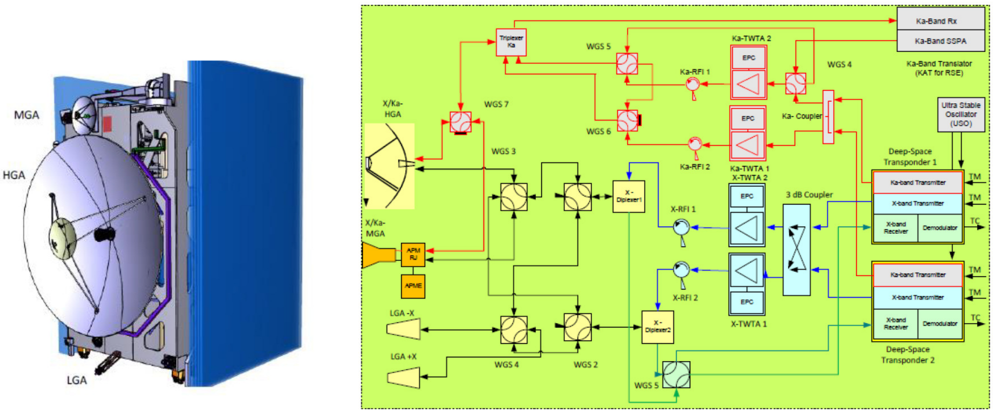

Fig. 4 Communication Subsystem and Antennas - Juice (Airbus Defence and Space) [9]

Fig. 5 Low-Gain Antenna - LGA (RUAG), Medium-Gain Antenna - MGA (SENER Aeroespacial) and High-Gain Antenna - HGA (Thales Alenia Space)

The other main system, and the mission core, is the payload or instrument. There is a large variety of payloads/instruments and, although an effort in standardisation has been done, most of the payloads are mission related and require a high degree of customisation. Currently, with the New Space emerging, fleets of high number of identical satellites are manufactured and instruments/payloads can also benefit from a mass production approach and certain level of standardization. In the case of telecommunication missions, the number of RF parts is extremely high and in the particular case of High Throughput Satellites (HTS), the numbers get close to thousands. Frequency re-use is one of the most commonly used strategies to boost the throughput. An example of this architecture is provided in Fig.6, where a high number of very similar RF chains is presented. Similarly to the example related to the communication systems presented before, components before and after the Low Noise Amplifier (LNA) and the TWT Amplifier, respectively, are critical in terms of high power handling and electrical losses. Due to this reason, RF parts are built using high performance transmission lines like waveguides. This translates into issues related to accommodation and mass, which are critical for missions such the one presented in [10]. Fig.7, which can be found in [11], is an example of a HTS where a high number of RF parts (waveguides, filters, switches) have to be accommodated. The reduction in terms of mass/volume in one of the designs could have a strong impact at payload level because of the already mentioned re-use of the same design multiple times. Sometimes, the volume/mass reduction does not translate into a payload volume/mass reduction but in the accommodation of a higher number or parts and, consequently, in the overall throughput increase in the case of, for instance, the HTS systems.

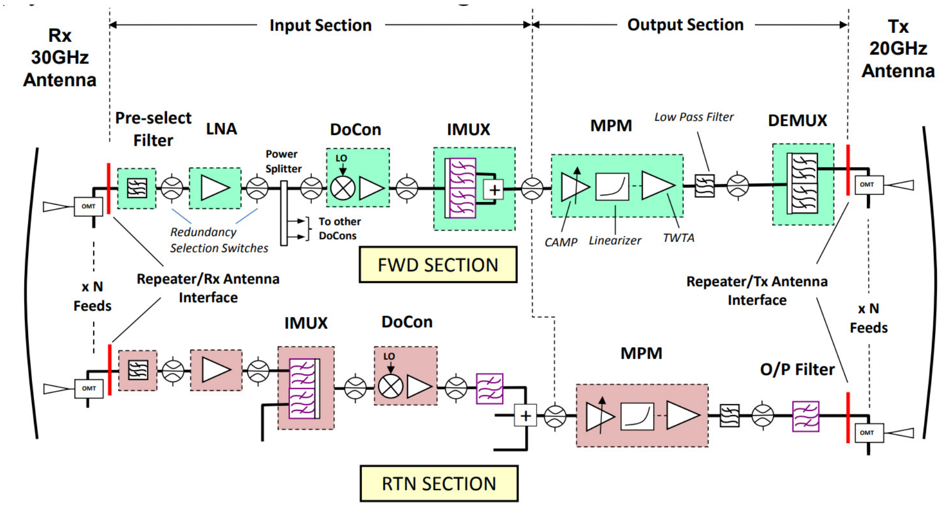

Fig. 6 Simplified Payload Block Diagram Using Conventional RF Equipment [10]

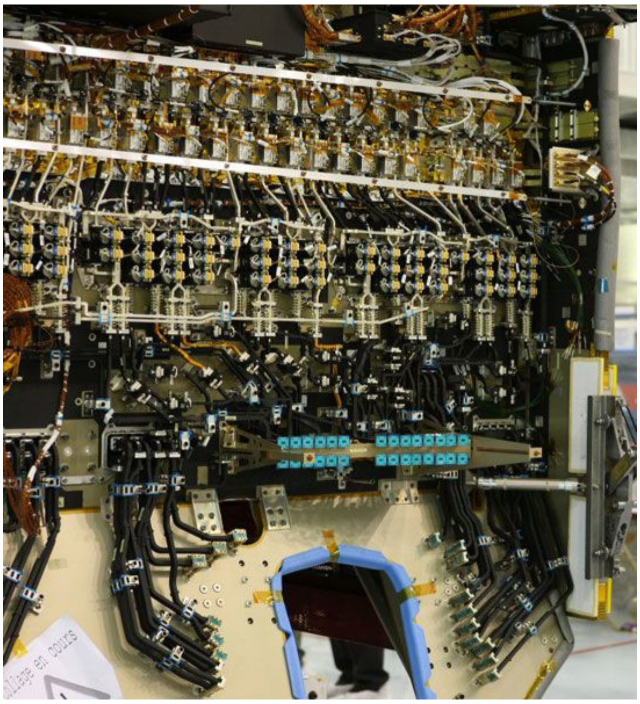

Fig. 7 Eutelsat's Ka-Sat view [11]

HTS systems, such the one discussed before, perform a high number of beams which translates into large antenna feed clusters like the one presented in [12] included in this paper in Fig. 8 (left). Complex RF designs result in the manufacturing and assembly of multiple parts. Complexity will be present also in other parts of the RF chain such as the filters, multiplexers or distribution networks like the ones presented in [13]. An example is also shown in the design from Honeywell in Fig.8 (right). It is pretty easy to conclude at this point that complexity comes at a price when using conventional manufacturing techniques. Evident penalties in terms of mass and size together with a potential RF performance degradation are frequently seen in this type of designs. In addition, it must be also noted the difficulty to manufacture certain designs when the waveguide profiles differ from the one that are best suited for milling.

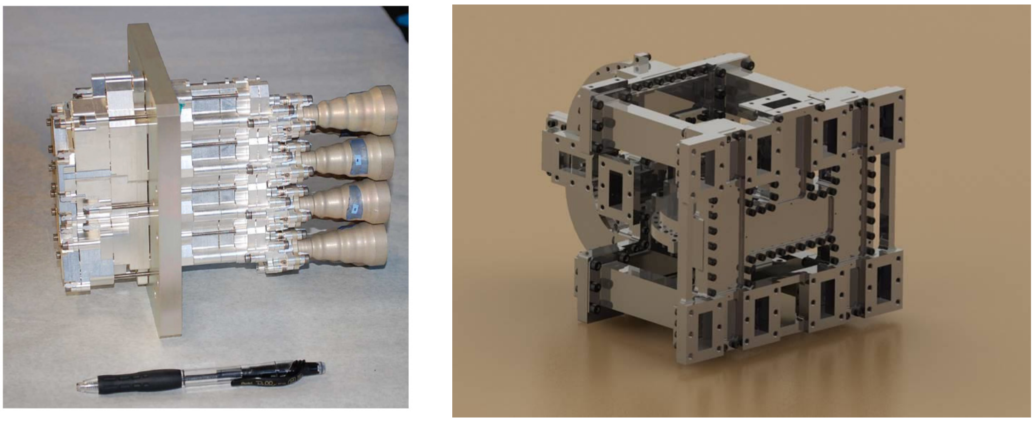

Fig. 8 Thales France Ka-band feed [12] // Honeywell Ku-band 8X8 Matrix Layout [13]

Waveguide filters, for example, are mainly based on rectangular or cylindrical cavities connected by irises. Cross-sections for the waveguide parts are dominated by the manufacturing technique to be used. The assembly is in the simplest case a clamshell structure and, in cases like dual-mode filters, an assembly of multiple parts that are attached by flanges and screws. Some examples of filters that have been built using conventional manufacturing techniques are shown in Fig.9. These two examples show the complexity regarding the manufacturing and assembly of this type of RF parts.

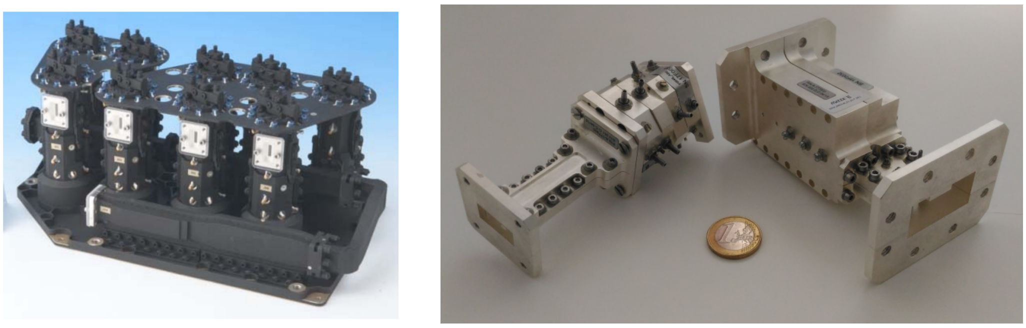

Fig. 9 Thales France Ku-Band Output Multiplexer (OMUX) - Vertical topology // RF Microtech C- and Ku-band waveguide filters [14]

The complexity (and its associated size/mass impact) increases exponentially when the RF designs move out from the conventional topologies. This is the case presented [15] and shown in Fig. 10, Fig. 11 and Fig. 12. The design decision to move to smooth profiles instead of conventional square ones was based on the great improvement in terms of high-power handling and, in particular, for multipactor aspects. These profiles, while providing an improvement for RF performance, increase the manufacturing challenges, which in most of the cases translate into a higher production cost. The lowpass filter has been fabricated using a simple clamshell topology where two identical parts have been manufactured in aluminium and later on silver plated to increase the electrical conductivity. As it can be noticed in Fig. 12, RF performance does not differ from the simulated results, which was an expected outcome since milling can provide accuracies around 10um.

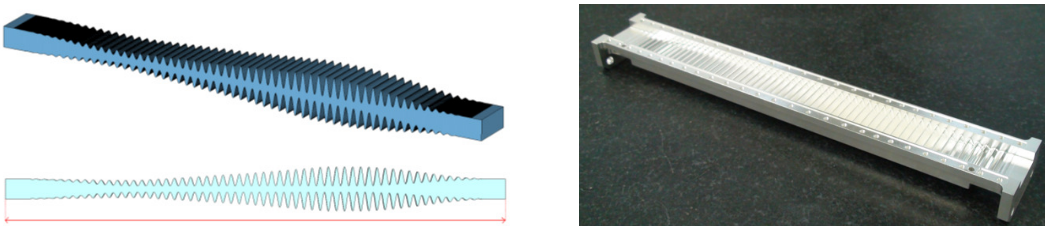

Fig. 10 High Power Waveguide Lowpass Filter with smooth profile - Electromagnetic design and half-size of milled structure [15]

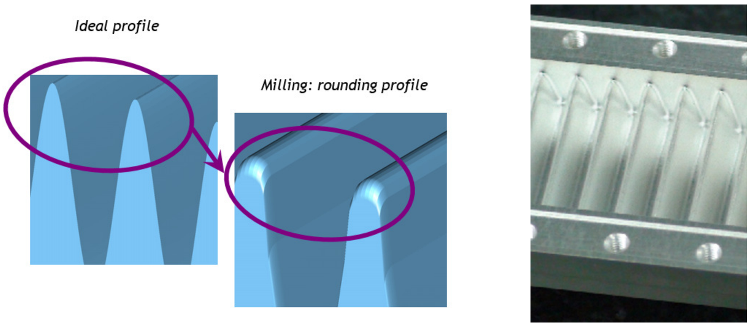

Fig. 11 High Power Waveguide Lowpass Filter with smooth profile - Design modification for milling manufacturing [15]

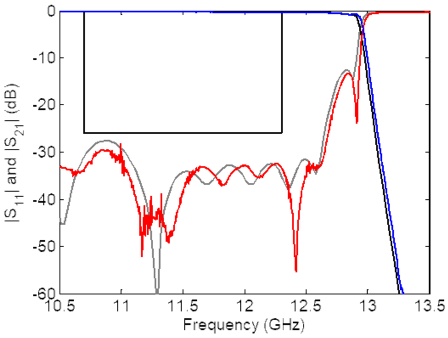

Fig. 12 High Power Waveguide Lowpass Filter with smooth profile - RF performance (grey/black: simulations and red/blue: measurements) [15]

As an alternative, a different manufacturing technique was also used for this type of lowpass filters based on smooth profiles. Electrodeposition is a multi-step manufacturing technique, that is well described in [16]. The process starts with the manufacturing of a mandrel that corresponds to the empty area inside the filter, as shown in Fig. 10 at the left side. Once the mandrel is manufactured, the next step is the electrodeposition. The process requires an electric current that passes between two electrodes (an anode and a cathode) immersed in a conducting electrolyte containing metallic salts. The anode is usually a bar of the metal being used for the plating and the cathode is the mandrel. Therefore, the metallic ions contained in the solution are converted in to atoms on the cathode surface, and these build up micron upon micron to produce an exact replica of the shape of the mandrel. Electroforming can fabricate a device in just one piece if the component includes a single mandrel. Moreover, the thickness of the deposit can be easily controlled, and different materials, such as nickel, copper or silver, can be used to grow the deposit. The material thickness can typically vary between 0.01 to 0.5 mm with a shape deposition rate defined around 10 microns per hour. Finally, after the desired electrodeposition has taken place, the final electroformed component is separated from the mandrel. To do this, the mandrel is dissolved within a chemical solution, leaving behind the finished device.

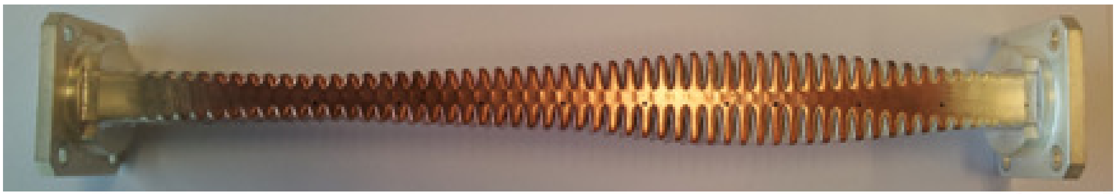

Fig. 13 High Power Waveguide Lowpass Filter with smooth profile - Electroformed waveguide filters [15]

RF performance of the electroformed filter was good and comparable with the one obtained with milling. A further analysis of the electroformed filters, using X-Ray Computed Tomography was performed to assess the internal surface quality of the finishing. In general, it was observed that there were some bubbles in the solid inner side (depicted in Fig. 14). These bubbles could even (in some cases) crack the surface up to certain point and have some influence on the frequency response.

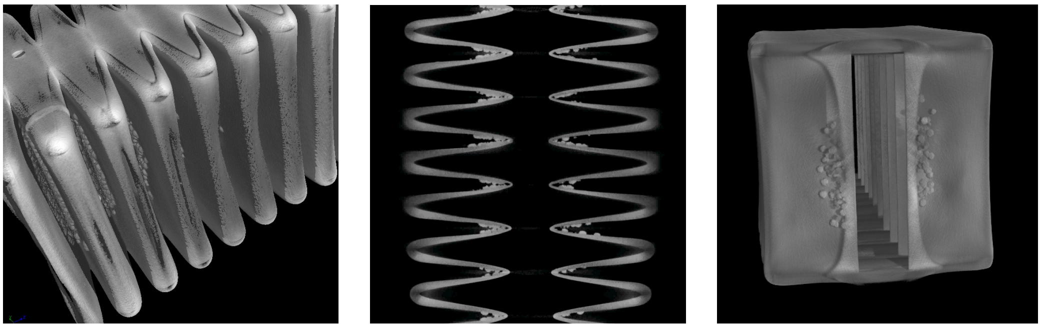

Fig. 14 High Power Waveguide Lowpass Filter with smooth profile - Computerised Tomography (CT) Scan in electroformed parts [16]

At this point in time, the reader can already answer some questions regarding elements that can benefit from an 3D printing process and which are the most suitable materials to be used to build the parts. As a general philosophy, additive manufacturing should be used only if it brings added value in terms of performance or cost. It is worthy to highlight here that RF designs are very constrained by the classical manufacturing and assembly techniques. Added freedom in the manufacturing approach will be for sure welcomed by RF designers and, as a wish from this paper's authors, will trigger the constant progress of RF design tools to deal in an efficient way with RF concepts much more evolved than current ones.

The number of RF parts that can benefit from a 3D printing approach is extremely high. Some examples of parts that could benefit from a 3D printing approach have been described in this chapter together with the major justification for the use of a 3D printing process. The freedom is not only limited to the design freedom (RF and 3D) but also regarding the available materials. Metals are still preferred to polymers for space application. However, new alloys and improved polymers are being widely investigated for their use in space and, here the beauty comes, the suitability of the new materials for 3D printing process is also being investigated.

As an important remark, RF performance is mainly driven by the material that interfaces with the electric fields. This is why it is common to apply a metal coating of materials such as silver or gold with the purpose to reduce the ohmic losses. This is an easy task when the manufacturing is performed in multiple pieces while it becomes a very difficult process when mono-block structures with internal cavities are built. Alternatives will be discussed in next chapter.

4 Ohmic Losses Reduction Techniques

Ohmic losses play a critical role in microwave passive parts such as filters, antenna feed parts or simple waveguide runs. In the case of the receive chain, losses before the LNA will have a direct impact on the system performance in terms of the Noise Figure. Ohmic losses in transmit chains will affect the overall Effective Isotropic Radiated Power (EIRP) and will contribute to the temperature increase due to the percentage of dissipated power. When moving to higher frequencies, the ratio surface roughness vs. skin depth gets higher and the surface resistivity increases [17]. RF part size also tends to decrease at higher frequency, resulting in an increased power dissipation density and, hence, temperature rising. These issues are more critical in systems with limited space for the accommodation of modules, such in the case of satellite systems.

3D printing has emerged as a potential solution for complex RF/Microwave hardware where either an improved performance is required or stringent accommodation requirements are imposed. In [18] and [19], the cross-section of a Ku-band bandpass filter has been optimized in order to improve its Q-factor and to modify the out-of-band response, reducing the need for bulky lowpass sections. Due to the complex geometry, Selective Laser Melting (SLM) in an aluminium alloy has been chosen as the most suitable manufacturing solution. Unfortunately, the resulting surface roughness is much worse than in conventional parts manufactured by milling. Additively manufactured Ka-band feed components have been presented in [20]. Special attention has been paid to the position of the part inside the printing platform in order to reduce the manufacturing deviations and the resulting surface roughness. However, in this case roughness does not play a critical role since the design is broadband. Again, the preferred manufacturing solution has been SLM using an aluminium alloy.

Metal 3D printed parts present a rough surface that depends on the material characteristics and process parameters as reported in [21]. The scan speed was found to have the greatest influence in the surface roughness for a given flat sample and building direction. However, for complex structures, the orientation of the part with respect to the printing platform will have a paramount effect in the internal roughness. In cases where the resulting roughness of the manufactured part is not sufficient to meet the requirements, different strategies could be followed.

Surface smoothing by removing material has been largely investigated regarding 3D printed parts. However, it could produce a non-uniform material removal depending on the part geometry. In addition, the process is suitable for open geometries and it is difficult to apply in cavities with small and intricate geometries like the ones found in RF filters and antenna feed components.

Surface coating has been also proved as a good technique for improving the surface roughness by adding a metal layer with a thickness beyond some hundreds of nanometres. In addition, this metal layer could contribute to the loss reduction for the transmitted RF signal by selecting a material with low-loss resistivity such as silver or gold. Both electrodeposition and electroless deposition are extensively used with RF parts. However, thanks to the achievable layer thickness that can be obtained with electrodeposition techniques (tens of microns), it is currently the preferred solution for RF parts. Electrodes need to be located strategically in order to produce an adequate flow of current and, hence, an uniform material deposition in all areas. However, due to the discrete number of electrodes to be used during the electrodeposition process , and its position with respect to the part to be coated, the deposited layer could lack uniformity. As briefly described in [16], the relative position of the electrodes (anode) and the part to be coated (cathode) will dictate the variation in layer thickness. In waveguide-based RF parts, the number of accesses for the insertion of electrodes is limited and can easily result in a thickness variation of the deposited layer and a potential risk to get areas with layers below or comparable to the skin depth at the frequency of operation. This last effect will result in an increase in terms of RF insertion losses and potential Passive Intermodulation Product generation.

When considering complex structures typically manufactured using 3D printing, the electrode positioning within closed areas such as cul-de-sac structures is not trivial and could even become impossible. This section mainly focuses on providing an overview of the electroless coating process and its suitability for the plating of RF hardware.

Multiple techniques have been used for the deposition of metals on different substrates such as electrodeposition, electroless deposition, chemical vapour deposition, thermal evaporation or sputtering. Among all of these techniques, electroless plating has been a widely used technique in industrial sectors such as the aerospace or automotive sectors, the electronics, and renewable energy industries and others. Electroless deposition has become particularly attractive in the electronics industry where the use of non-conductive substrates (ceramics, polymers, metals, etc.) and the miniaturization of the circuitry present difficulties for other conventional techniques.

Electroless deposition is a versatile technique that does not require additional external energy, so the homogeneity on the coating prevails even in complexly-shaped objects following closely the part, and it can be used with non-conductive materials. Electroless deposition is an electrochemical deposition process that operates based on oxidation and reduction (or redox) reactions within the electrolyte.

The use of electroless plating in RF parts has been sometimes limited due to the need to work with water, which imposes constraints in terms of coating materials. The development of novel electroless plating techniques using ionic liquids has shown the capability to overcome these limitations. Ionic liquids (IL) form because the charge of the ions is delocalized and this gives rise to a reduction in the lattice energy. IL are metal-complex and, hence, offer the chance to develop novel electroless plating baths in electronics for coating polymers without the toxic and problematic organic complexants used in water. In addition, metals have significantly different reduction potentials in IL solutions compared to water. One important consequence of this characteristic of the ILs is that alloy coatings can be deposited more readily and that it should be possible to develop many novel alloy coatings. An example of a sustained galvanic coating of silver metal deposited on a copper surface from a non-aqueous IL is shown in [22]. In this case, the substrate material is copper and the process has been developed taking into consideration the need for uniform passivation coming from the Printed Circuit Boards. As a drawback, the resulting coating presents roughness 5 times higher than the one presented in the substrate.

There are challenges that still need to be faced in order to obtain a stable and ready-for-market coating process based on IL. For instance, the process is very sensitive to water contamination and an adequate atmosphere has to be created in order to prevent moisture. Under this scenario of absence of water contamination, the central advantage of using IL electrolytes in electroplating is that there is a negligible hydrogen evolution during electroplating, since these are non-aqueous solutions, and it is possible to deposit metals with superior mechanical properties. On the other hand, deposition could be performed in a controlled environment containing inert gases like nitrogen or argon. However, this approach currently has a high cost associated. Additional cost is related to the ionic liquid procurement per se.

High-power microwave parts operating in harsh environments will be exposed to high temperature levels and periodical variations. Adhesion between the different layers and substrate has to be granted during the entire operational life. Optimized process parameters and a convenient selection of any additional intermediate layer will play a crucial role to define consolidated electroless solutions suitable for space RF parts. In addition, pre-treatment steps could be considered to prepare the substrates and improve the adherence.

Qualification requirements of coatings for space applications are listed in [23], where it is specified a minimum set of durability requisites for coating use in space. Information is also provided about some mission specific tests (including the atomic oxygen test, thermal ageing test, air-vacuum test, and solar illumination test). In particular, in Table 5-3 of [23], the test matrix for the qualification of thick metallic coatings for RF and electrical application (and corrosion protection coatings) is provided.

When developing new baths, it is also important to keep in mind that directives such as REACH Annex XIV are increasingly adding chemicals used in plating baths to the list of substances which cannot be placed onto the market unless authorisation is granted by the EU.

RF equipment manufacturers have based their heritage in well consolidated electrodeposition techniques. It is expected to achieve similar RF performance (e.g. ohmic losses) with the new IL-based electroless coating techniques. In addition to the losses, Secondary Emission Yield is another parameter to be closely monitored for any potential solution since it will strongly impact the high power capabilities of the devices.

5 Additively Manufactured RF parts

There is an extensive literature for microwave devices where additive manufacturing has been used as the building technology. However, a big amount of the existing references are conventional or, let us call them, traditional designs with some small modifications in order to make them ”printables”. Most the improvements have been achieved in terms of mass and volume but not so much improvement has been achieved from the RF performance point of view yet. The root cause for this lack of improvement and, in some cases, degradation, is manifold. First, and as it was already anticipated, printed parts are sometimes just a modified version of the already existing one that has been optimized for conventional manufacturing methods. A second reason is the lack of understanding of the end-to-end manufacturing process where 3D printing is one of the steps to achieve the final RF part. For instance, roughness can have a high impact in terms of electrical losses, which will also have an effect in the thermal behaviour of the RF part in case high power operation is required. The understanding of the manufacturing process is crucial for the RF part optimization but it also requires to look at the design from all possible perspectives: cost, number of parts, thermal aspects, mechanical aspects, compatibility between process (e.g. with surface coating).

Next, some examples regarding the use of additive manufacturing for building RF parts will be described. The examples are related, as much as possible, with the RF function review provided in previous chapters.

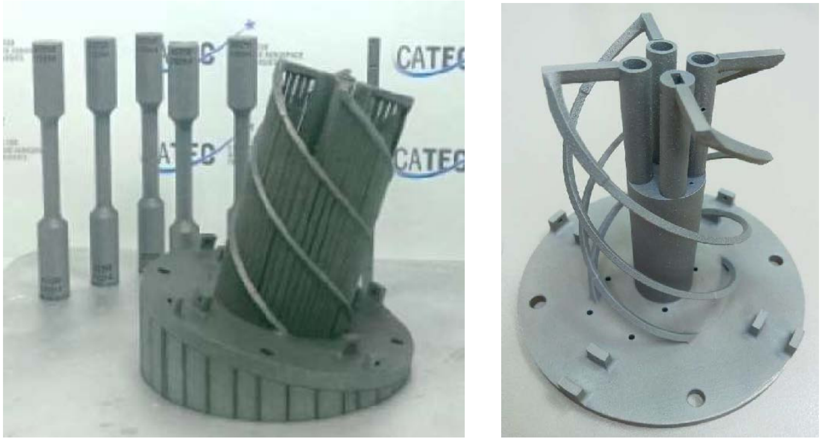

Fig. 15 3D printing S-band helix antenna (SENER Aeroespacial) [24]

The first example is related to the S-band antennas that are commonly used in the Telemetry, Tracking, and Command (TT&C) subsystem that can be found as part of the platform system. This is one of the possible design concepts and it is particularly interesting for a 3D printing approach because of the metal wire implementation. Shape/position are closely related to performance. There is not a single way to manufacture this type of antennas and providers are offering solutions considering an inner support, milling, applying electroforming or using Printed Circuit Board (PCB) techniques to define the metal tracks. Due to mechanical aspects, the robustness of the structure is a key parameter. The antenna shown in Fig.15 was developed under an ESA General Support Technology Programme (GSTP) contract by SENER Aeroespacial and presented during the second ESA Industry Days: Additive Manufacturing for RF/Microwave hardware [24].

The topology was optimized in order to reduce residual stresses during manufacturing while minimising the mass. In addition, the contact with the support structure was reduced by optimising the cross-section of the helix. The manufacturing was performed by CATEC using classical AlSi10Mg aluminium alloy. Several samples were built simultaneously using the same platform for further material characterisation. Sandblasting was applied in order to improve the surface roughness. The model has been subjected to a qualification test campaign including vibration, shock and RF tests showing good stability of the performance. In addition, the company has developed an internal standard to ensure the repeatability of the part for the different serial numbers. The deformation of the presented part has been studied for different manufacturing orientations and support distributions and a 45-degree angle is selected to minimise these two aspects. It is important to mention that the antenna works at relatively low frequency (S-band) and parameters such as roughness are less critical than at high frequencies (beyond Ku-band).

Another example, also linked with the previously discussed HTS telecommunication systems, is presented in [25]. The paper introduces a 18-feed Tx/Rx antenna cluster operating in Ku-band. Multiple functions are integrated in a single block including the horn, Orthomode Transducer and waveguide routing. Waveguide cross-sections were modified in order to avoid sharp corners. The resulting circular or elliptical cross-sections were more suitable for the manufacturing using SLM. The performance was in good agreement with the simulations. A picture of the manufactured part is provided in Fig. 16. The paper does not include information regarding silver plating or any other passivation process. Thermal or mechanical aspects are not discussed and, when implemented, they could have an impact in the current design (e.g. unforeseen stresses due to any structural support).

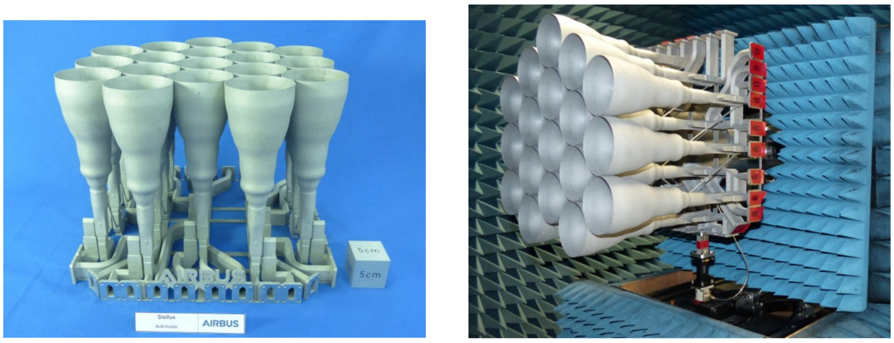

Fig. 16 Ku-band antenna cluster (Airbus Defence and Space) [25]

The same group has recently presented another paper [26] for a radiating element integrating active components. In conventional HTS telecommunication systems the required power was in the order of a few hundreds of Watts. Nowadays, aiming an optimum exploitation of the throughput, active antennas perform a large number of high gain antennas. As the service areas become much smaller, also the antenna gain becomes much higher and so the power per channel can be reduced. The horn, polarizer and housing for the amplifier were printed as a single monolithic block as can be seen in Fig. 17. The material used was the standard AlSi10Mg alloy. Similarly to the previous example from the same authors, the presented prototype is mainly focused on to RF aspects. In this particular case, where the active RF part is integrated together with the radiating element, thermal design is deemed critical since it could strongly impact the RF design as well. Though it is considered as a great contribution toward the integration of active and passive functions in a single block, this paper shows an early phase of the development and additional work is expected to increase the Technology Readiness Level (TRL).

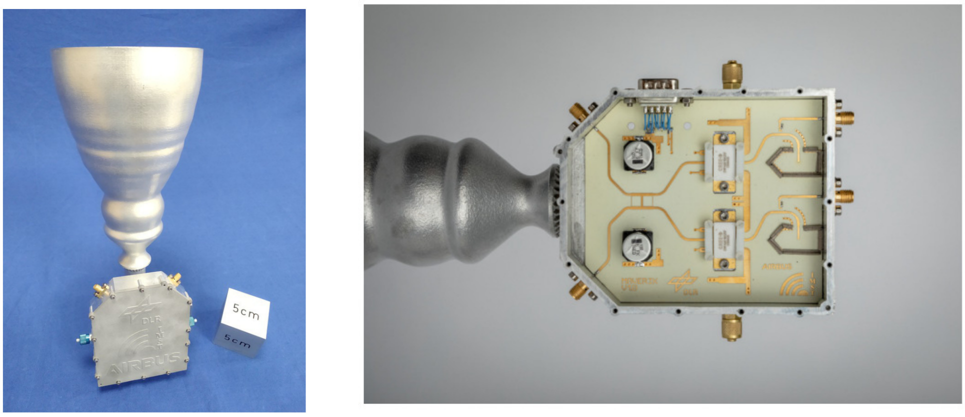

Fig. 17 Ku-band antenna cluster (Airbus Defence and Space) [26]

The same manufacturing technique was used for an ultra-lightweight lowpass filter. As it can be seen in Fig. 18, the smooth profile has been designed in such a way that the structure is self-supported when being printed in vertical direction. This avoids the need of support structures in the inner part that would directly impact the surface roughness and that are difficult to remove. Powder from the hollowed wall has been removed using dedicated hole. In opposition to the previously presented 3D printed parts, this filter performed a sharp transition the between pass-band and stop-band, which makes the structure sensitive to manufacturing tolerances. The differences in roughness depending on the surface can be easily appreciated in Fig.19. The structure has been built with the smooth surfaces facing down in the printing platform. Indeed, the increased surface roughness is due to the classical hanging effect in SLM processes. This is also an effect to the taken in account during the design phase.

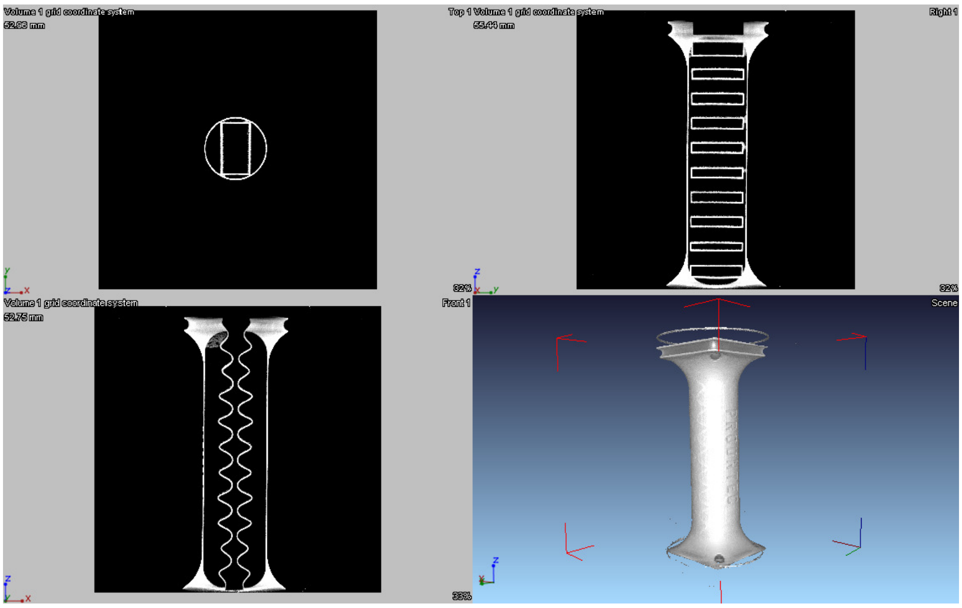

Fig. 18 lightweight 3D Lowpass filter - Computerised Tomography (CT) Scan - UPNA internal research

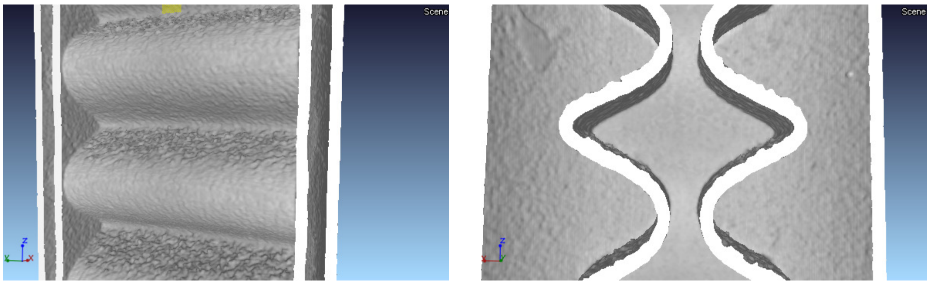

Fig. 19 lightweight 3D Lowpass filter - CT Scan - Roughness - UPNA internal research

The examples presented so far are based on commercially available 3D printers using metals. All share the same constrain, which is the need of support structures in cases where, due to the complex inner shape of the cavities, the angle of the down-facing regions in any internal critical area goes beyond the process limits. This severely impacts the surface roughness and, in some cases, it can make the manufacturing impossible. This is particularly true at high frequencies where the size of the cavities is such that the introduction of internal support parts is not possible. Among others, Metal Binder Jetting (MBJ) has been studied due to its capacity to reach high resolution while providing a low surface roughness. A good comparison with respect to SLM is shown in [27] and it has been included in Fig.20. This paper reports a remarkable roughness resulting from a MBJ process, which is 1/5 the one using SLM.

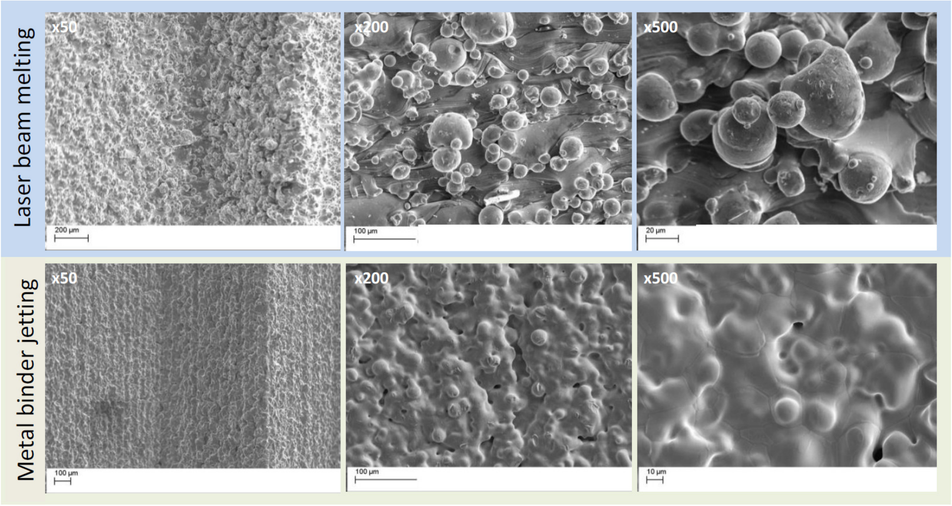

Fig. 20 MBJ and SLM roughness - Qualitative comparison [27]

In MBJ, parts are built layer by layer, by applying a binder on each metal powder layer. Printing takes place at room temperature in a building box that does not require any protective atmosphere. No supports are needed, since no melting takes place during printing. The surrounding powder provides enough support, which facilitates de-powdering and reduces the need for post-treatment. Then, the 3D printed components are taken out of the powder bed. All loose powder is removed and reused. Finally, the printed components are sintered to gain density and correct material properties following existing standards. Printing and heat treatments are separate processes, allowing for a wide selection of materials. Each process step can be optimised for each material. Some aspects regarding the process are described in detail in [28] and one good example of the use of this process is introduced in [29]. Process parameters such as powder characteristics, layer thickness, binder saturation, drying time, print orientation, and print speed affect the density and strength of the binder jetted part. Also post-processing steps to obtain desirable material densities need to be considered.

A drawback of this technique is that the part dimensions can be difficult to adjust, due to the big dimensional changes during sintering (30-40% volumetrically, 15-20% linearly). Unfortunately, Metal Binder Jetting is nowadays still restricted in terms of material choice. The most common alloy used for this process is stainless steel 316L, which was thus selected to conduct preliminary tests. On top of the electromagnetic properties, several other analyses were conducted such as Computerized Tomography (CT) scan, roughness, hardness, microscopy, X-ray fluorescence (XRF) and Coefficient of Thermal Expansion (CTE) analyses in dedicated samples, including RF filters. The manufacturing was performed by CETIM. Printing parameters such as layer thickness, width of the printhead and space between nozzles are reported in Fig. 21. These parameters are based on CETIM know-how and they have been taken as an initial reference for the process assessment regarding its suitability for RF parts.

A relative density of 7.64 [g/cm3] was measured. The 316L alloy density ranges from 7.87 to 8.07 [g/cm3]. By considering that the average density of this alloy is 8.0 [g/cm3], it means that the filter would present a 4.5% porosity.

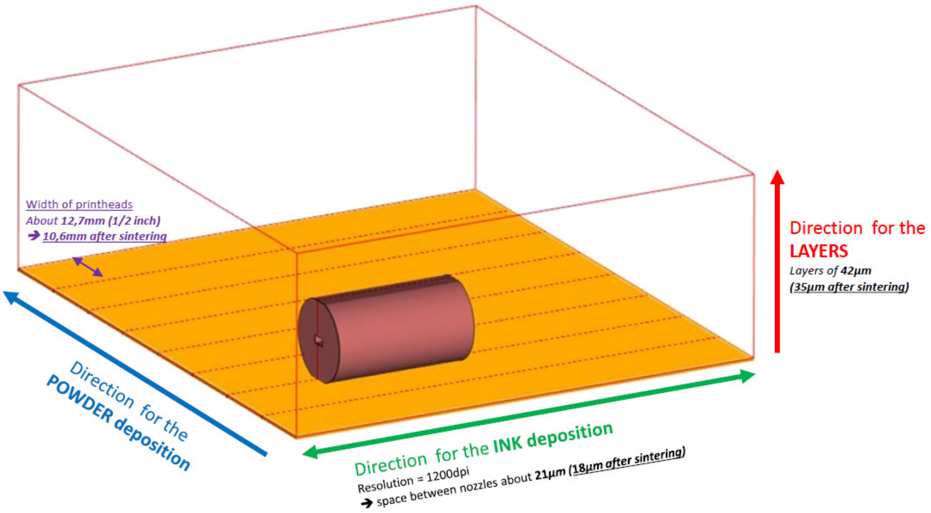

Fig. 21 MBJ paramters used during the printing at CETIM facilities - UPNA internal research

Measurement of the RF performance of microwave filters can be used as a way to check the accuracy of any manufacturing process. For this purpose, four filters have been designed at different frequency bands. These four filters are just scaled versions of a filter design to operate inside the frequency range of the WR22 standard. Dimensions of internal geometries get smaller as the frequency of operation is increased. The filter designs have been modified in order to provide enough room for the de-powdering phase, which is performed before sintering and deformations can be easily induced. A 3D view of the parts is provided in Fig. 22. A picture of the manufactured parts is provided in Fig.23. The parts where printed in an horizontal position. Same position was selected for the sintering and interfaces were later on re-worked in order to achieve a flat surface for the flanges to be used during the RF characterisation.

An initial check was performed using CT scan and it is presented in Fig. 24, confirming that the waveguide profile was well built.

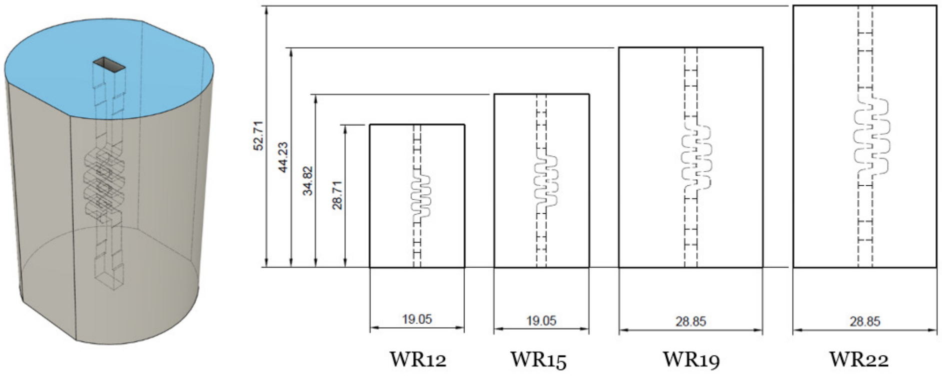

Fig. 22 3D view of the lowpass filter designs and maximum dimensions - UPNA internal research

As an example, the transmission frequency response of the WR22 filter (the largest one) is presented in Fig.25. The responses of the filters have shifted up to higher frequencies while the bandwidth is not considerably modified. The shift toward higher frequencies has been also found in the WR19, WR15 and WR12 filters, increasing as the frequency band is higher. Taking the measured values as reference, the WR22 RF design has been pre-distorted by using for each axis

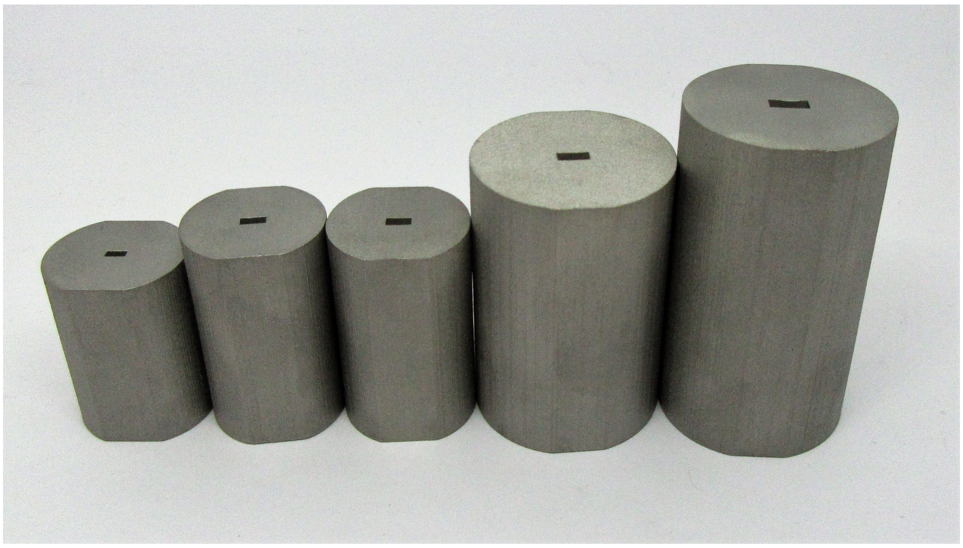

Fig. 23 Manufactured parts using MBJ - UPNA internal research

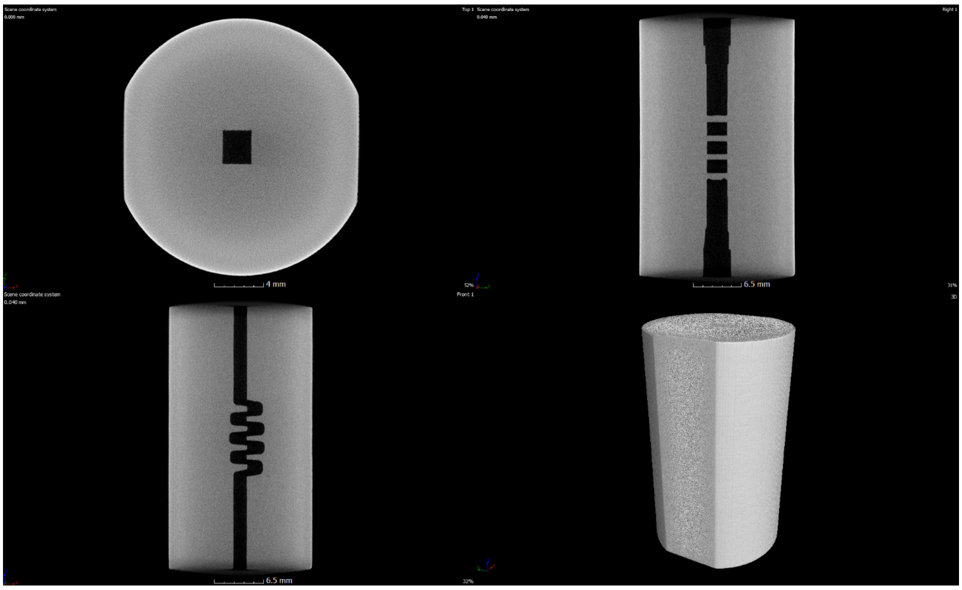

Fig. 24 CT Scan for the MBJ filters - UPNA internal research - Test performed at the European Space Agency

a different factor. The measured results has been obtained when the [0.97, 1.01 and 0.89] scaling factors are applied in the X, Y and Z axis. The X and Y axis correspond to the filter cross-section while the Z-axis is the longitudinal direction between the flanges. Very similar scaling factors have been applied for the other filters in order to reproduce the target measured results. This means that distortion is related to the filter geometry.

In a new manufacturing run, dimensional pre-distortion will be applied to the designs. The amount of pre-distortion is calculated based on the deviation on RF performance. The availability of software tools for the shrinkage prediction could avoid the need of two manufacturing runs. Electroless gold plating will be performed in order to reduce the ohmic losses, inherently high for the selected building material.

This chapter has shown some of the current RF developments where 3D printing has been selected for the manufacturing of the parts. An important take over from the previous chapters was

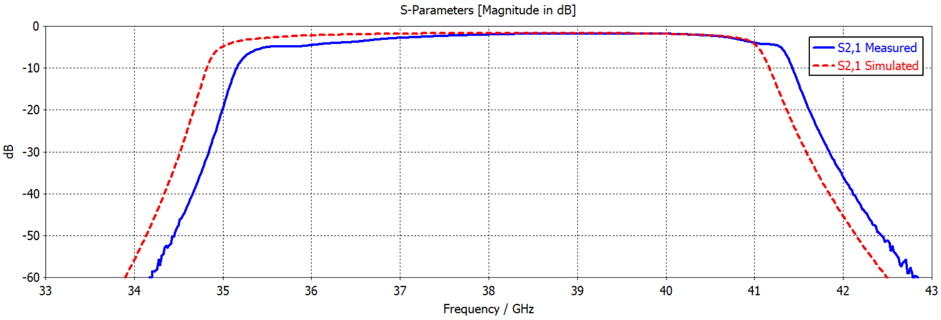

Fig. 25 RF response (S11 and S21) - Simulated and Experimental data - UPNA internal research

the identification of the driving requirement(s) which justify the use of a 3D printing approach instead of conventional ones. Mass is one of the main drivers for space applications and the provided examples are pointing in the same direction. The manufacturing in single (or a reduced number of) parts will for sure contribute to the volume and mass reduction. In addition, aspects such as RF losses due to multiple interfaces, generation of passive intermodulation products due to multiple junctions or high level of systems integration can be also improved when considering 3D printing. Unfortunately, at high frequencies, there are still difficulties to obtain excellent RF performance (e.g. low roughness). However, flanges can be removed which will contribute to improve the RF performance at high frequencies. This is one of the UPNA's study drivers from the on-going study on MBJ technology.

For large and complex multi-function sub-systems, it is recommended to find a set of functions where the integration in a single block will bring some benefits but, at the same time, it is still possible to manufacture with the selected 3D printing process. This means than, for example, using 3D printing for a single building block may not bring a lot of benefits but it could be advantageous if we integrate more surrounding functions in the single block.

6 Conclusions

Industry working in the development of RF parts has received 3D printing as fresh air. Though it was just used at the beginning to replicate already existing designs, new concepts have been lately developed. But there is still room for improvement. The evolution of new materials and processes is very fast and is feeding the machinery for the production of the future generation of RF parts. Somewhat we should understand the material and manufacturing processes as additional variables in our designs.

A good understanding of the space environment and the portfolio of 3D printing processes (and associated materials) is paramount before starting any evaluation regarding the RF part and its potential manufacturing using any 3D printing approach. Then, the main constrains/requirements of the payload need to be defined (e.g. power handling, Effective Isotropic Radiated Power (EIRP), accommodation, thermo-mechanical aspects). The driving parameter(s) for the design of the RF parts or subsystem must the selected from the set of constrains/requirements. This is a fundamental step to increase the chances to get improvements with respect to any reference part/subsystem which is manufactured using a more conventional approach. Though it is good to look at the reference models (e.g. previously manufactured parts) it is also convenient to take as the reference the new set of specs, which must already include the goal in terms of improvement.

The RF part or sub-system can integrate multiple functions in a single block to be manufactured by 3D printing. This will result in a complex design that, providing it can be manufactured, could bring great benefits in terms of performance (RF, thermal and mechanical), mass, volume and power handling, among others. However, specifically for RF parts working at frequencies beyond X- or Ku-band, the coating with materials such as silver is mandatory. However, the silver coating of complex parts can become a challenge, or even not possible, with conventional electro-deposition techniques. New metal coating processes are under development in parallel to the development of 3D printing processes as a response to a current need for metallisations of complex RF parts.

Each 3D printing process provides advantages but, at the same time, has constrains. The good understanding of the 3D printing processes will contribute for the selection of the most suitable one for each RF application. As mentioned during the paper, one of the main drivers for the RF parts is the surface roughness, particularly at high frequency. Manufacturing processes such as Metal Binder Jetting are under investigation and MBJ seems to be a promising solution when the roughness is the main driver for the design.

However, particularly for space, there is a need for consolidation and creation of certain heritage. In this sense, the European Space Agency is working in the generation of European Cooperation for Space Standardization (ECSS) standards to provide industry with guidelines for the validation/qualification of processes, materials, and parts. Priority has been given to [4] - ”Processing and quality assurance requirements for metallic powder bed fusion technologies for space applications - ECSS-Q-ST-70-80C Rev. 1”, since this is the preferred manufacturing solution for space applications. The standard can be already obtained from the ECSS website. This standard specifies the necessary requirements to perform metallic Powder Bed Fusion processes for space applications. Though this standard is specific for metallic powder bed fusion technologies, the approach defined in the standard can be easily extended to other manufacturing techniques in order to define the hardware requirements, check the compatibility with the selected 3D printing process, define an end-to-end manufacturing route and verify properties for both the resulting material and the final product.

From this paper, the authors would like to finish this paper encouraging the research groups to add the word ”smart” in their new design approaches. This is not a way to be pretentious with wording but to remind that RF designers are key players to do it better. Let’s talk about Smart Digital Manufacturing for RF parts!.

7 Acknowledgements

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