SAFETY OF FLIGHT APPROACH FOR FUEL TANKS ALM FLANGES FOR TILTROTOR APPLICATION

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Abstract

Additive Layer Manufacturing (ALM) is a very promising manufacturing technology, which makes possible to produce components that would not have even been possible just a few years ago. Metal powder additive manufacturing produces three-dimensional parts layer by layer. This allows for almost a complete freedom of design and it overcomes the traditional limits of subtractive manufacturing techniques, such as CNC. The design process can also incorporate the use of topological optimization software, making it also possible to obtain higher integration with respect to machined parts, thus minimizing the number of components to be assembled, with advantages in terms of material waste and energy consumption. The present paper intends to be an overview of the approach which aims to guarantee the safety of flight of metal Additive layer manufactured parts of the fuel storage system of a Civil Tilt Rotor Technology Demonstrator under development in the framework of EU Clean Sky 2. Since the flight tests are already scheduled, the technologies that will be taken on-board will reach TRL6 at least. The parts under investigation are the metallic flanges, which connect the fuel hoses system to the fuel storage system (which are bladder tanks installed in the wing bays). A flowchart of the testing activities, aiming to guarantee the safety of flight, is presented, along with manufacturing, experimental and NDI results.

1. INTRODUCTION

Additive manufacturing (AM) is receiving exceptional attention from the mainstream media, investment community, and national governments around the world. Large aerospace companies, such as Boeing, GE Aviation, and Airbus, are hard at work qualifying AM processes and materials for flight, as well as NASA and Aerojet Rocketdyne have been recently testing rocket engine components made using additive manufacturing [1].

Among the different classifications - which terminology is stated by ASTM F2924-12 standard - the powder bed fusion is one of the most promising technology branch for metallic AM [2]. It comprises Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Selective Laser Sintering (SLS). Additive Layer Manufacturing (ALM) is a very promising manufacturing technology, which makes possible to manufacture components that would not have even been possible just a few years ago. Metal powder additive manufacturing produces three-dimensional parts layer by layer. The method relies on a digital data file being transmitted to a machine that then builds the component. This allows for almost a complete freedom of design and it overcomes the traditional limits of subtractive manufacturing techniques, such as Computerized Numerical Control (CNC) machining. As an example of full potentiality of metal AM techniques, one promising application is the production of meta-materials with a prescribed microarchitecture (lattice structure), enabling new lightweight solutions.

The design process can take successfully

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advantages from topological optimisation methodologies to determine the more fruitful material distribution, thus the resulting components are both light and strong. AM makes possible to obtain higher integration with respect to machined parts, thus minimizing the number of components to be assembled, with advantages in terms of material waste and energy consumption connected to the production cycles (one step for fully integrated parts). From waste material and environmental point of views, the powder consumption is minimal, since it encompasses the powder needed for the part, the supporting structure and some entrapped powder. The excess of non-melted powder is removed during the cleaning phase and it can be, theoretically, re-cycled. Due to limited building envelopes of AM systems, the production of large structural elements by AM is restricted, but significant improvements are coming on the market [3].

AM in aircraft industry began by introducing the technology mainly for noncritical parts such as ductwork and interior components, or engine components, like the GE Leap engine fuel nozzle, for which, in Oct. 2018 GE Aviation's manufacturing plant in Auburn, Alabama, celebrated its 30,000th 3D-printed fuel nozzle tip [4].

Undoubtedly the full integration the new technology in the aircraft industry will be when AM structural components will replace the current made with traditional (e.g. CNC). In September 2018 Airbus officially launched the production of latch shafts for the doors of A350 XWB passenger aircraft using 3D manufacturing [5]. A spoiler actuator valve block was additively manufactured by Liebherr-Aerospace for an A380 and this was the first additive manufactured flight control hydraulic component flown on an Airbus aircraft [6]. According to the latest 2020 news, there is an expansion in the number of use cases where additive could give a clear advantage with respect to conventional methods in manufacturing components for commercial and military aircrafts. An example is the use case of an US airliner, which has substituted the wingtip fences of its Airbus A320 current engine option (A320ceo) aircrafts with additive manufactured parts, due to difficulties in having the cast version of the parts [7]. Recently Air France KLM was granted approval by EASA to use Additive Manufactured parts under part 21J process, having until now certified 12 parts to be flight ready and fitted on airlines. Also Etihad first received EASA approval to 3D print with filament technology in 2017 and was one of the first in the world to certify, print and fly 3D printed cabin parts [8].

Coming to structural parts, Spirit AeroSystems, which manufactures fuselages for Boeing commercial aircraft, has recently begun installing the first titanium structural component (a back-up fitting for an access door latch) made through additive manufacturing, for the Boeing 787 [9].

Despite the real benefits associated with AM processes, there is still a big challenge in certification of AM parts for the aeronautical industry, due to a lack of an established certification roadmap and qualified materials. Aircraft companies are developing their own material property data, a process that is very expensive and time consuming. This is the reason why their proprietary information are not shared with the broader aerospace community, thus resulting in variability and a lack of material and process standards [10]. Consequently, the certification and qualification of AM parts is the most difficult stage for the aircraft industry to handle since it means to have sufficient quality data related to AM parts within the regulatory frameworks of the certification authority. The most significant barriers to AM parts certification are constituted by the AM technology limitations (instability, difficulty in modelling the process, inherent defects, low precision and resolution, limited build size and slow build rate) and by confidentiality of AM designs and processing data (lack of database and standards, lack of design guidance, lack of quality assurance methods and Intellectual Property issues). In addition, the adoption rate of the technology is slowed down by other factors such as the special personnel needed to manage such technology and the high cost of equipment and materials.

In recent years, companies, government agencies, and consortiums in the aerospace industry are working collaboratively to develop the appropriate frameworks and guidelines to the standards.

There has been some progress in terms of the development of the standards related to AM both in general and in the aerospace industry: there are over a dozen organisations involved in the process of development of these standards (such as ASTM and ISO on the general aspects of additive manufacturing, SAE more on the aerospace field, and government organisations such as NASA to provide guidelines) [11].

Several memoranda and notices related the certification of AM parts and the use of the technology in the maintenance and alteration of aircraft components have been issued by EASA and FAA [12], [13]. According to EASA FAQs [14], additive manufacturing is still considered "new technology", this is the reason why concurrent effort among the main players and stakeholders continues with periodic workshops on the topic. One of the results of these workshops and the public consultation process launched by EASA, is the contribution to the recently issued EASA Certification Memorandum - Additive Manufacturing, CM–S-008 Issue 03 (Apr. 2021), intended to be used in conjunction with Aerospace Industry Association Recommended

Guidance for Certification of AM Components [15].

The EASA CM–S-008 includes content specifically focused upon the 'first step', i.e. applications of no or low criticality parts. The repeated message from the regulators to industry is regarding the need to take a 'step by step' approach with respect to the safety-criticality of AM applications. Individuals or organisations responsible for the design of the AM part should pay particular attention to some aspects connected to the process, before starting the dialogue with the Authority, such as understanding of the criticality of the application; identification of the Key Parameters and demonstration of understanding of the sensitivity of the engineering properties important to the safety of the final parts; statistical coverage of engineering properties important to safety; appropriate transfer of knowledge and control.

The present work regards the application of this promising technology, intended to be used as innovative feature of the bladder Fuel Storage System (FSS) of a tilt rotor technology demonstrator, under development in the framework of EU Horizon 2020 Clean Sky 2 [16]. The tilt rotor is the Next Generation Civil Tilt Rotor Technology Demonstrator (NGCTR-TD), developed by the Work Area Leader (WAL) Leonardo Helicopters, which is planned to perform the first flight tests in 2023 . In particular, the AM technology is applied to some metallic venting flanges of the FSS, located in the wing structure [17], [18]. All activities have been developed within Clean Sky 2 DEFENDER project [19], which aims at qualification and manufacturing, up to flight, of the fuel storage system of the NGCTR-TD.

The technology held by the DEFENDER Consortium is Electron Beam Melting (EBM) [20], which has been developed to process titanium alloys, in particular Ti6Al4V, as well as materials that require elevated process temperatures. Concerning the Ti6Al4V, the EBM process shows several advantages, such as good dimensional accuracy and repeatability [[21]], a fine resultant microstructure and good static and fatigue properties, very low residual stress, and no oxygen contamination (thanks to the vacuum environment in which the EBM process occurs) [22]-[24]. At the beginning of the project it was investigated the opportunity of realizing some flanges of the fuel storage system of the NGCTR-TD by using the EBM technology, nevertheless a back-up solution relying on CNC is available in case issues arise to take the AM flanges to flight.

2. REQUIREMENTS AND MOTIVATION

Metallic parts in the bladder tanks have to comply with different functions. They constitute the interfaces between the tank itself and the fuel gauging and distribution system. The main requirement they have to fulfil is the compatibility with fuel. Due to the fact that they are in contact with fuel, they shall possess adequate corrosion resistant characteristics or suitable protection as well as a suitable value of electrical conductivity for bonding. In addition, they shall guarantee no fuel leakage at the interface with the other components of the fuel storage system and the fuel piping, this is typically accomplished with the use of o-rings. All the Fuel Storage System, including the AM flanges, has also to be crashworthy [25]. The AM part itself has to guarantee no fuel leakage also from a porosity/ internal defects point of view, which is known to be inherent to the process. Moreover, it has to be investigated, from process point of view, if internal defects propagate under typical vibratory environment encountered by the vehicle. Once the defect thresholds are identified by combining mechanical test and NDI on “fit and form” fully representative specimens, the components for flight need only the NDI inspection. If the NDI gives internal defects higher than the threshold the part is discarded or needs further investigation, conversely it is considered cleared for vehicle installation and next for flight.

Leonardo Helicopters and DEFENDER consortium have drawn a path to the Safety of Flight needed for Permit to Flight for this peculiar and innovative application, which, to the authors' best knowledge has not been disclosed by available literature worldwide.
According to the above requirements and considering cost and time constrains of the project, the path agreed to guarantee the safety of flight (it is the first of a number of experimental flights of the NGCTR-TD) has been drawn starting from the need to identify the acceptable maximum defect size with respect to permeability and vibration. This activity is framed inside a broader Acceptance Test Procedure (ATP) for the ALM flanges intended to be used for the FSS.

3. SAFETY OF FLIGHT APPROACH

The route to Safety of Flight is articulated into three main bullets, which are propaedeutic each other:

1) Identification of the acceptable maximum defect size versus permeability
2) Identification of the acceptable maximum defect versus vibration
3) Acceptance of the components for flight.

The first bullet, shown in Figure 1, is conducted at coupon level. In particular, the ETSO-C80 [26] permeability test foreseen for flexible fuel and oil cell material was adapted to the AM specimen. Critical thicknesses were selected and no. 3 coupons for each selected thickness, were produced by EBM technology and finally tested. All the permeability specimens were investigated by means of Non

Destructive Inspection (NDI) by Computer Tomography (CT), in order to detect internal defects (collected by dimensions and topology). After that, the permeability test was conducted and results recorded. Negative tests leads to a process parameters tuning to reduce the internal defects (number and dimensions). In case of success, the detected defects are classified as acceptable from a permeability point of view, and the second phase can be performed (vibration).

The second phase is aimed at investigating if the internal defects which are in the full scale parts are propagated by the vibration environment or triggering of new defects happens under such environment. To this aim, a suitable number of flanges (having identical geometry and interfaces with respect to the flanges that are intended to be taken to flight) was manufactured with EBM: no. 3 identical items for each Part Number. All full scale test articles were scanned by CT and internal defects dimensions and topology was recorded. The flanges were then subjected to vibration tests. Visual inspection and changes in their dynamic response characteristics were the first checks performed just after vibration. After vibration test, a new CT was performed on the test articles, and the internal defects dimensions and topology was recorded and compared with the same information picked before the test. If the analysis returns that the original defects are not propagated nor new defects triggered as a consequence of the vibration, the level of defects detected in the flanges, is considered acceptable as a threshold to perform the acceptance of the parts. In case propagation or triggering is detected, process parameters are tuned to reduce the internal defects (number and dimensions). The 2nd phase is shown in the diagram of Figure 2.

The third and last phase pertains the Acceptance Test Procedure of the flight articles. After the manufacturing of the flight articles, which foresees also the production of a suitable number of tensile specimens to be mechanically tested, all the AM flanges are scanned with CT, and internal defects are recorded and compared with the maximum allowable size evaluated in the first two phases. The item is accepted, if detected defects are lower than the threshold evaluated in the first two phases. If the defects are equal or slightly higher than the threshold, a deeper analysis is necessary to understand if these defects can affect the Safety of the parts. This analysis is based on engineering judgement on the location of the defects versus the stress levels predicted by FEA or, if necessary by higher fidelity non-linear crack propagation analyses. The tensile tests results executed on the coupons relative to the production batch are employed to tune the finite elements model used during the design stage and to assess if experimental data are conservative or not with respect to the design material allowables. Former activities on mechanical characterization were already carried out by the consortium on the comparison of the strength performance of the material between “as built” and “machined” condition of the coupons [27]. In case the experimental data are not conservative with respect to those used for design, a deeper investigation on the material properties versus the process parameters is needed. The flowchart of the ATP is depicted in Figure 3.

4. MATERIALS AND METHODS

The coupons and test articles are manufactured by using a GE Additive ARCAM machine type A2X (Electron Beam Melting) with a working volume of 210 x 210 x 380 mm. The Laboratory is equipped with a Powder Recovery System (PRS) to recover unmelted powder and with a software for the preparation of the building file (interface between CAD systems and 3D printing systems). The Lab machine is able to treat Ti6Al4V powders. The Arcam A2X system is designed for production of functional parts within aerospace, as well as general industry for a wide range of materials [28]. The build chamber of the Arcam A2X is specifically designed and built to withstand extremely high process temperatures, up to 1100° C and to avoid the leakage of ionising radiation generated during the process. The process foresees a first phase in which the build file is prepared through software, and in parallel the machine is prepared for the job, with the loading of the powder tank and all the consumables needed. The build file receives as input the 3D (Standard Triangulation Language - stl) file of the part to be manufactured. The manufactured parts have been defined by means of a topological optimization and detailed FE analyses per-formed by in-house and commercial codes (ABAQUS v62.0). The STL file is the starting point to prepare the build file. The main phases of the build file foresee: a fixing phase in which any issue in the input file are solved; a check that the stl part fit in the chamber and the evaluation of the most suitable position for manufacturing; a slight scaling-up to take into account thermal shrinking during cooling and finally the generation of the wafer supports.

Computer Aided Tomography on components under analysis was performed by a specialized supplier. The equipment used is a GE Phoenix v|tome|x m tomograph micro-focus tube suitable to scan highly absorbing materials. Data are acquired and elaborated by Phoenix Datos| x 2.0 software, and the reconstructed 3D volumes exported in 32bit files and visualized by Volume Graphics Studio MAX 2.2 software, with power of 91 W. Scan parameters: voltage 260 kV; current 350 μA. Resolution and sensitivity 84 μm. The scan was aimed at detecting both internal porosity (voids) and areas of different density (e.g. cavities filled with unmelted powder). The result of the CT scan are expressed in terms of total number of detected defects, percentage of porosity i.e. ratio between total porosities volume and scanned material volume; maximum size of the defect i.e. the diameter of the sphere circumscribing the maximum defect; quantitative analysis of inclusions i.e. material with different density with respect to the surrounding material, e.g. cavities filled with unmelted powder.

For what concerns the permeability test, the EASA ETSO-C80 has been adapted by substituting the flexible tank structure material with AM coupons in the shape of disks of different thickness. Permeability cups were placed in a suitable rack in a constant temperature of 20°±5° C, and a relative humidity of 65±10% percent. After allowing 1 hour for equilibrium, the cups were weighed to the nearest 0.005 gram and placed in the rack with the faces of the cups facing upward (test disks up). The cups are kept at the above constant temperature for 24 hours, then weighed to check for seal integrity. The cups are then in-verted (test disks down) in a rack that permits free access of air to the test disks. Cups are weighed after 1, 4, 6, 8, 11 days of reversal with a Radwag PS600.X2 precision balance. The diffusion expressed in fluid ounces per square foot per 24 hours equals the gram loss of the test specimen per 24 hours multiplied by a factor K. The result is the permeability measured value which in the present case was measured with respect to the eighth day and with respect to the eleventh day. The requirement from the ETSO is a measured value of permeability lower than 0.025 fluid ounces per square foot per 24 hours for each sample tested.

As far as vibration is concerned, a test campaign was performed on no. 3 samples of each part number (a total of 9 test articles) by applying the most demanding test condition between Helicopter and Fixed-Wing according to RTCA DO-160G [29]. To measure the dynamic response and detect the possible resonances during the resonance search, five micro accelerometers were applied on the flanges (PCB accelerometers models 352A71, 325C23, 356A01, 356A16). According to test specification, the test sequence involved the following steps:

- Fixture verification - shaker in Out-of-Plane (OOP) configuration, Sine sweep on Z axis
- Fixture verification - shaker in In-plane (IP) configuration, Sine sweep on X and Y axes, sequentially
- For each set of three flanges: Sine sweep on each axis; Sine on Random vibration test at Performance level on each axis; Sine on Random vibration test at Endurance level on each axis
- Visual inspection after the conclusion of the test on each set, to find possible structural failure

Sine sweeps were performed by using the vibrating table TIRA TV 59335-440 with the closed-loop control H/W SIEMENS LMS SCADASIII SC 310 and SC 310, in turn managed with TEST Lab Environmental S/W Sine module ver. 17. In order to perform sine sweeps in Z direction, the Equipment Under Test (EUT) was installed with the mechanical interface on the head expander of the shaker in OOP vertical configuration.

The Performance and Endurance sine on random vibration tests were performed by using the vibrating tables TIRA TV 59335-440 with the closed-loop control H/W Vibration Research 8500, in turn managed with Vibration View S/W Sine on Random module ver. 2016.

5. RESULTS

Permeability disks manufactured for this experimental campaign showed a porosity percentage which is within the typical range of EBM process, nevertheless the maximum defect size was higher than typical values of the process. The Permeability tests were indeed successful, since measured permeability was less than 0.025 according to ETSO-C80. Figure 4 shows the permeability disks and the cups used for the test.

After permeability tests, the campaign on the full scale test article was initiated. In Figure 5 the 3D CAD image of the three venting flanges under investigation is depicted.

Two EBM runs were launched for the production of the nine test articles, plus no. 3 tensile coupons for each run, for mechanical properties characterization. After cleaning and supports removal, the flanges were milled in the interface areas with the vibration test fixture and helicoil inserted to allow mechanical fastening on the fixture, Figure 6.

The Computer Tomography on the nine flanges showed a porosity percentage which is within the typical range of EBM process, nevertheless the maximum defect size was higher than typical values of the process. Moreover, a large number of defects was detected, Figure 7 is an example of the voids detected by CT on one of the test articles.

After Computer Tomography, and activity was started aimed at obtaining a fine tuning of the process in order to lower the number and dimension of defects. Nevertheless, exploiting the presence of such defects, the vibration test campaign was decided to be performed, in order to detect if any of the detected defect was propagated. Figure 8 shows one of the test configuration: the three test articles are mounted on the text fixture, which is in turn bolted on the vibration table. The test fixture is a thick plate having as requirements the ability to mate with the test articles and the vibration table and head expander, and a minimum natural frequency of 2000 Hz, in the configuration bolted on the vibration plate / head ex-pander and without flanges mounted on it.

The test rig requirements were investigated by means of Finite elements analysis. The characterization test on the fixture confirmed the theoretical prediction of absence of structural resonances and dynamic modal participation up to 2000Hz. The Vibration test sequence, agreed with the Leader, foresaw, for each set of three flanges and for each axis: a) Sine sweep; b) Sine on Random vibration test at Performance level; c) Sine on Random vibration test at Endurance lev-el; d) Sine on Random vibration test at Performance level; e) Sine sweep. For each set, at the completion of the test sequence, the flanges were visually inspected and no evidence of structural failure of any internal or external component was found. Furthermore, from the comparison of FRFs obtained from sine sweeps tests, performed before and after each test sequences, no relevant modification in flanges structural resonances (such as shift in resonance frequencies or change in transmissibility values) were evidenced, in Figure 9 one example of FRF comparison before and after Sine on Random sequence, for sine sweep Z case.

After vibration tests the flanges were scanned again with Computer Tomography and the activity is still work in progress, in order to verify if defects propagated as an effect of the vibrational environment.

In the meantime the fine-tuning of the EBM process gave as results a trial production with zero defects, which is a good starting point to proceed with the roadmap traced till the beginning.
It is envisaged the publication of detailed works dedicated to the CT scanning activity and Vibration, which will complement the philosophy work presented herein.

6. CONCLUSIONS

In the present paper a path to the safety of flight of additive manufactured metal parts of the fuel storage system of a tiltrotor technology demonstrator, under development in the framework of EU Horizon 2020 Clean Sky 2, has been presented. The technology investigated is the Electron Beam Melting (EBM), using titanium alloy powders. The path to Safety of Flight is built around the experimental activity of identifying, with respect to the innovative and still non-conventional manufacturing process un-der investigation, the acceptable maximum defect size with respect to permeability and vibration requirements. These two experimental phases are framed inside a broader Acceptance Test Procedure (ATP) for the ALM flanges intended to be used for the fuel storage system of NGCTR-TD. The flowchart of the procedure foresees three phases, the first one devoted to define the acceptable defect with respect to fuel permeability, the second one with respect to vibration environment. The third phase is the Acceptance Test Procedure, which will be used to accept the parts for experimental flight (Permit to Flight). The three phases foresee the execution of non-destructive tests on coupons and articles by means of Computer Tomography, and a set of tests such as permeability according to EASA ETSO-C80 and Vibration tests according to RTCA DO-160G. The methodologies and some preliminary results were shown, nevertheless the analysis of propagation of defects under vibration is still ongoing. This step is necessary to evaluate the minimum acceptable defects size for Acceptance purpose. Further works on the detailed aspects of the tests will follow as soon as the activities will be concluded.

7. ACKNOWLEDGMENTS

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9. FIGURES

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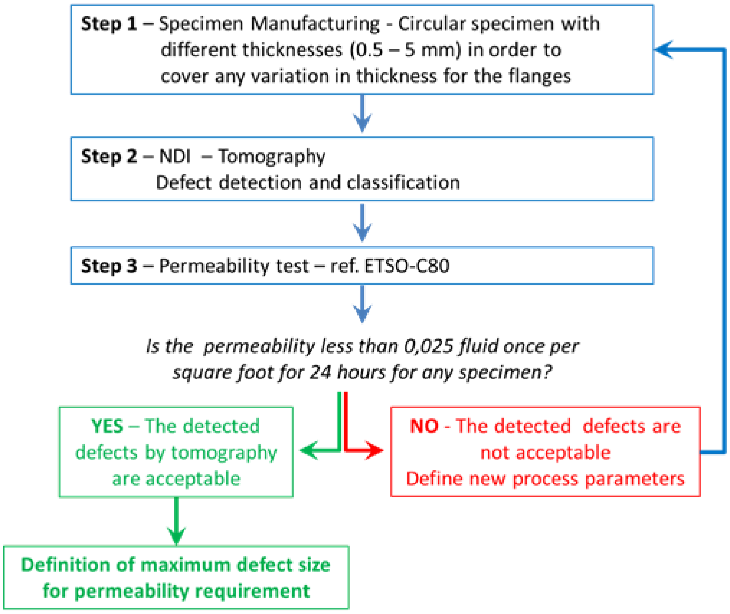

Figure 1 Phase 1 Identification of the acceptable maximum defect size versus permeability

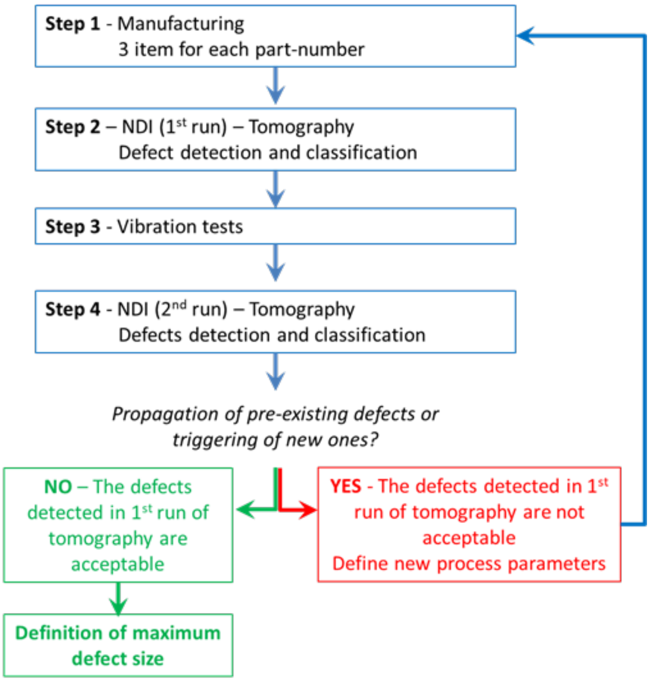

Figure 2 Phase 2 Identification of the acceptable maximum defect versus vibration

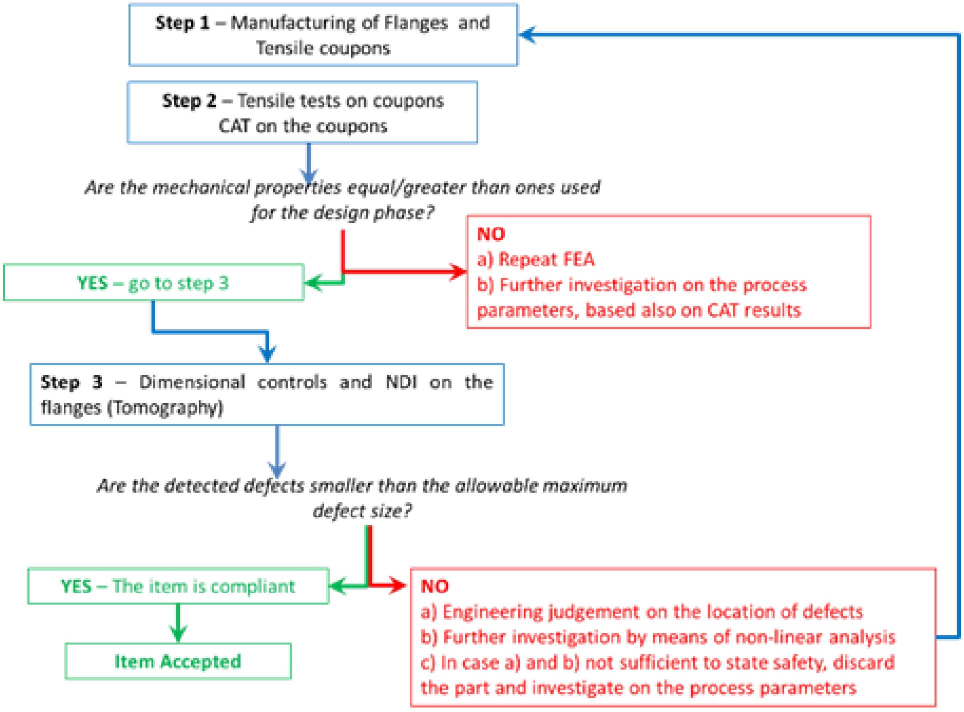

Figure 3 Phase 3 Acceptance Test Procedure

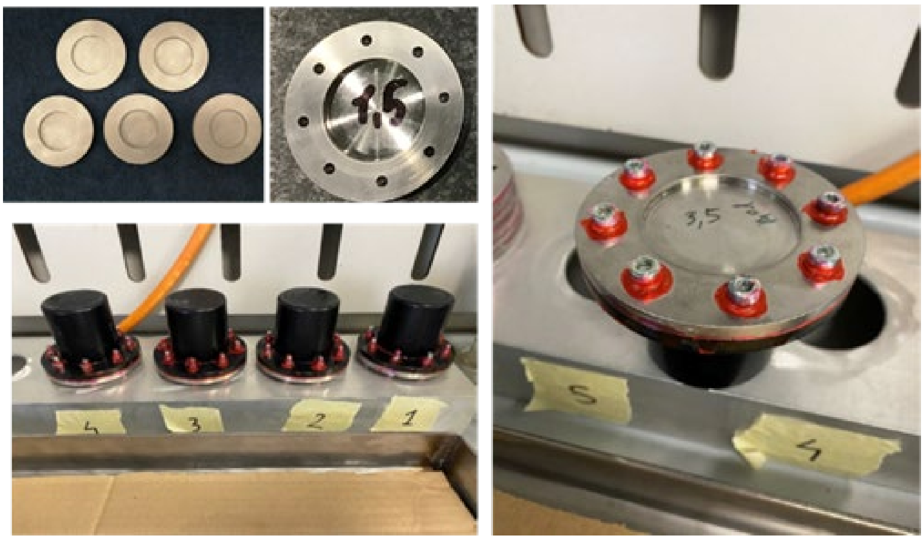

Figure 4 Permeability test

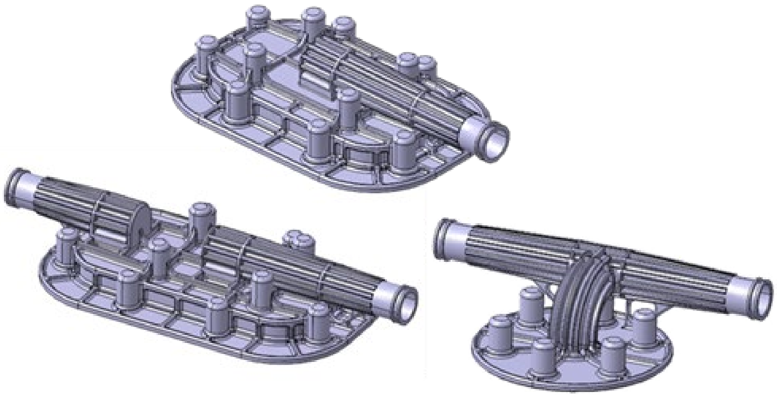

Figure 5 3D model of the test articles

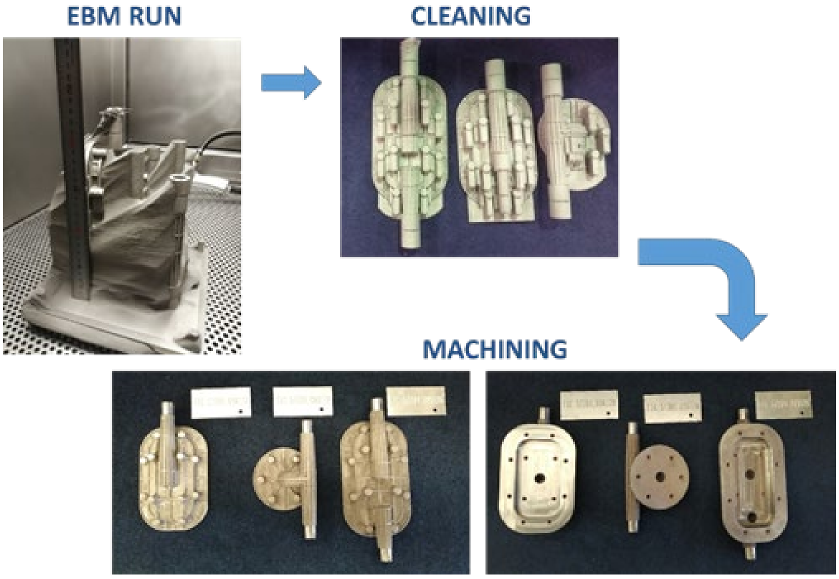

Figure 6 Test articles manufacturing steps

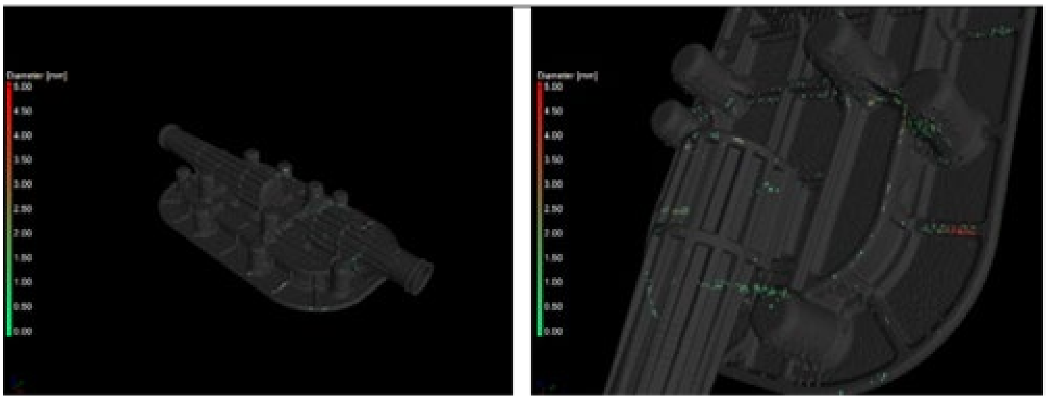

Figure 7 Computer tomography on one of the test articles

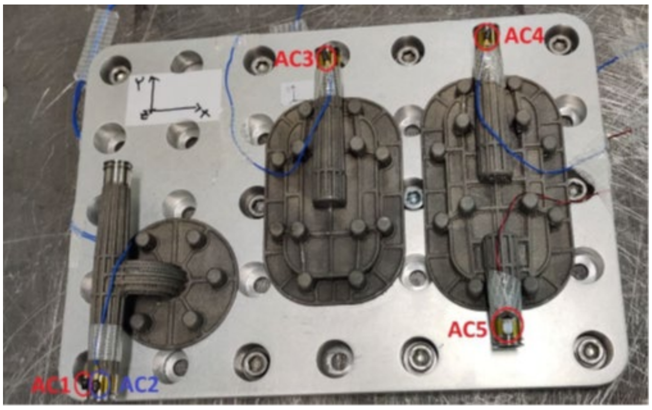

Figure 8 Test articles and fixture configuration before vibration test

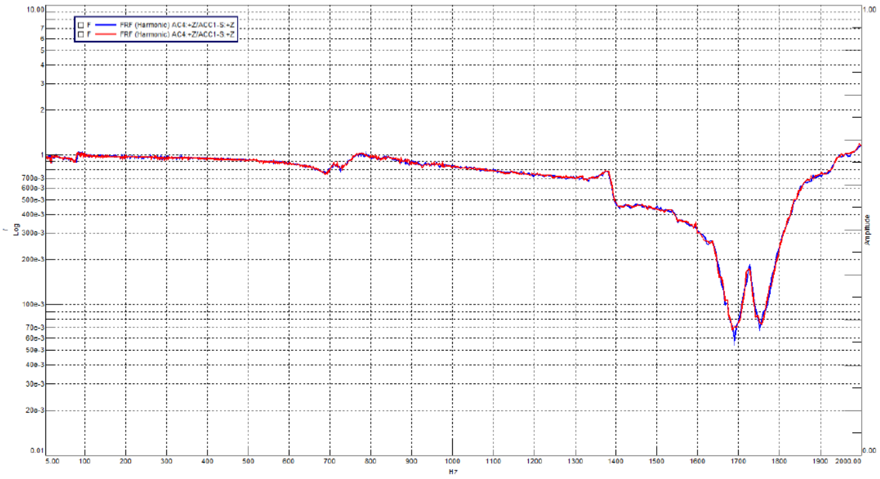

Figure 9 Sine sweep Z: FRF before (blue) and after (red) Sine on Random sequence