IN-SERVICE INSPECTION OF AERONAUTICS PARTS PRODUCED BY ADDITIVE LAYER MANUFACTURING (ALM) - in the framework of Bionic Aircraft project (GA nº 690689)-

INSPECCIÓN EN SERVICIO DE PIEZAS AERONÁUTICAS REALIZADAS POR FABRIACIÓN ADITIVA (FA) – dentro del marco del proyecto Bionic Aircraft (GA nº 690689)-

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ABSTRACT

Bionic Aircraft is a project founded under the H2020 Framework Program and it is a result of a need to reduce emissions due to the impact of the growth of the aviation industry. The introduction of Additive Laser Manufacturing (ALM) to produce some metal aircraft parts is considered as an opportunity to address this issue. This technology allows to produce ultra-lightweight and highly complex parts (so-called “bionic parts”).

One of the actions to consider in the project is the development of new NDT strategies to inspect, in-service, parts produced by ALM made of Al-based alloys. This need arises because, ALM processes for these alloys are at low maturity level (TRL2) and hence, no proven and certified NDT methods are yet developed. Moreover, in-service inspection of aeronautic bionic parts involves challenges like the uncertainty of the inner inspection of a layered material, the lack of accessibility (the part is attached to the aircraft fuselage), and the expected defects under in-service conditions, something still under study.

The objective of this work is to assess the inspection, in-service, of this kind of parts, by selecting and customizing the most suitable NDT methods, according to the type and maximum tolerable damage sizes estimated by a fatigue life prediction evaluation.

RESUMEN

El proyecto Bionic Aircraft, en desarrollo dentro del programa marco H2020, surge de la necesidad de reducir las emisiones derivadas del sector aeronáutico. La fabricación de ciertas partes metálicas de los aviones mediante Fabricación Aditiva (FA) se considera como una oportunidad para contribuir en esta reducción, con el cual es posible fabricar piezas ultraligeras y de formas muy complejas (piezas biónicas).

Una de las acciones dentro del proyecto, es el desarrollo de nuevas estrategias de END para realizar la inspección en servicio de piezas fabricadas por FA basadas en aleaciones de Al. El uso de la FA en estos tipos de aleaciones se encuentra en un nivel de madurez bajo (TRL2), lo que implica que actualmente no existen métodos certificados de END. A parte de dicho problema, la inspección de piezas en servicio conlleva más retos, como la particularidad de la estructura interna del material, la falta de accesibilidad (ensamblada en la estructura) y el desconocimiento del tipo de defectos que aparecen durante su uso.

El objeto de este trabajo es evaluar la viabilidad de inspección en servicio de estas piezas, seleccionando y adecuando los métodos de END más apropiados, teniendo en cuenta el tipo y el tamaño máximo de defectos estimados por la predicción de la vida útil en fatiga.

1. Introduction

Bionic Aircraft is a project founded under the framework H2020 and it is a result of a need to reduce emissions due to the impact of the growth of the aviation industry. Since ALM plays and important role in the development of new-resource-efficient manufacturing, the project is focused on developing and implementing the ALM in all stages of an aircraft life cycle, with the objective of enhance resource efficiency (1).

ALM (so called 3D-printing), can produce more cost-effective and lighter parts, together with the ability of improve production efficiency. Mainly, to manufacture metallic parts, Laser Beam Melting (LBM) is used (2) (Figure 1,a). Melting metal powders layer by layer offers geometrical freedom that cannot be achieved otherwise. Moreover, parts produced by ALM fulfil different product requirements within a single building process, saving process steps and enabling lower costs compared to the conventional production (3).

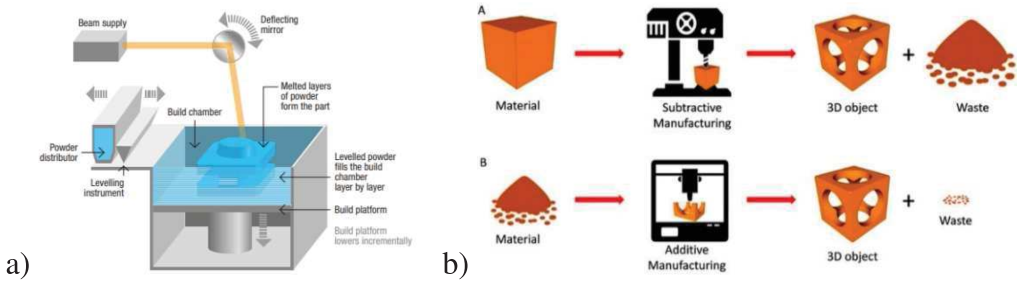


Figure 1. a) LBM process (2); b) Differences between CNC and ALM (4)

Hence, in summary, ALM allows to produce ultra-lightweight and highly complex parts (bionic parts), as well as to reduce the material waste (Figure 1,b) (1). Mainly, materials like steels, Ni- and Co-based superalloys and Ti and Al alloys are used (5). The use of Ti alloys, for example, supposes a weight reduction of 40% (compared with one Al aircraft part manufactured by conventional milling) and the wasted product is less than 10%. In case of Al-Li based alloys, the weight reduction is even higher (50%) (1).

1.2. Potential defects and the need of new NDT strategies

Nowadays the ALM processes for Al-based alloys are at low maturity level (TRL2) (6). Within this framework, one of the actions to be considered is the development of new in-service NDT strategies of parts produced by ALM. Moreover, in-service inspection of aeronautic bionic parts involves challenges like the uncertainty of the inner inspection of a layered material and the surface quality, the lack of accessibility when the part is attached to the fuselage, and the expected defects produced by in-service conditions.

Microstructures generated from these processes can be more complex than conventionally processed parts. The use of mobile heat sources can result in significant microstructural heterogeneity. In the specific case of ALM, the microstructure can lead to rectangular partitions of elongated grains bound by equiaxed microstructures (7). That complex structure generates uncertainties regarding the behavior of acoustical waves.

Lack of accessibility is another challenge to overcome, since the part is installed in the structure, damages in inaccessible locations appear and non-visually inspectable small or subsurface cracking may form (8). The accessibility of some sensors must be also studied.

Typical defects produced with additive manufacturing processes are listed in some research articles (5, 9, 10) but they are assumed to be detected in-process or in-line. So that, only defects that appear or grow during in-service life of the part will be searched in the scope of these work, which are different from the defects detected in previous stages. The defects can be located either on the surface, associated with corrosion process, fretting, handling damage, etc, or inside the material, linked to manufacturing erros such as hot cracks (11).

Considering that the inspection of ALM parts needs new NDT strategies and adding the challenges related to in-service inspection, this work is focused on assessing the inspection feasibility of bionic parts made of AlSiSc, selecting the most suitable NDT methods, according to the damage information obtained by a fatigue life prediction study.

2. Methods

In this section, different steps are described to carry out a screening of potential applicable technologies. The screening has been designed based on previously identified challenges. The reference demonstrator to perform the study, selected during the project, is the bionic jack actuator bracket (Figure 2).

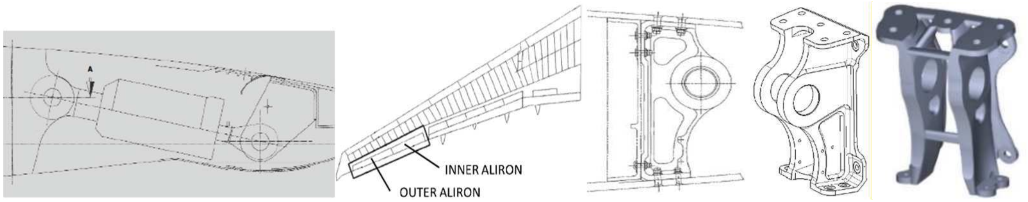


Figure 2. (left) common design and assembly (right) new bionic part.

2.1. 1st screening: bibliographic analysis.

This screening allowed to avoid technologies that although they are nowadays used, they are not suitable for in-service inspection. Bibliographic information about existing NDT methods for additive manufactured materials, the physical properties of ALM materials, and information of current NDT methods used to inspect similar parts were considered.

Large number of references were found in the bibliography, but X-ray based techniques and ultrasound (US) were the most mentioned to detect inner defects. For sub-superficial defects detection, Thermography was the most referenced, together with Eddy Current.

The most relevant physical properties of ALM materials in terms of inspection give a clue to select technologies to inspect inner defects. A grain size of ~50µm (12) is obtained with cellular or columnar grains, depending on the built direction. Considering that the grain noise is a problem when the grain size of the material is larger than $\lambda/10$, the relation $\lambda=c/f$ with c=6250m/s (longitudinal velocity of Al), gives that the upper limit for the frequency is 12,5-15MHz. In terms of macrostructure, grain size of ~200µm (12) is obtained. Regarding surface quality, if it is treated or not, different values are obtained.

Nowadays, after manufacturing, similar parts are inspected by using both X-ray Computed Tomography (CT) (internal defects) and Dye Penetrants (surface defects).

Considering all this information, although CT seems to be the most suitable NDT method, it cannot be applied for in-service inspection, because access to both sides of the sample is required. Likewise, any method involving oversized or heavy equipment are not viable due to accessibility limitations. Therefore, US seems to be the most suitable technology to detect inner defects, since small equipment and one inspection access are required. In terms of surface/sub-surface defects, besides the Thermography, Computer Vision (CV) will be also considered due to its reliability for automatic surface inspections.

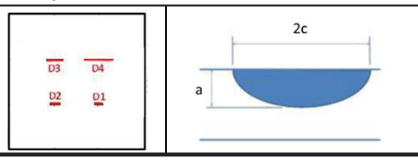
2.2. 2nd screening: lab-scale testing on simple reference specimens. Surface quality and internal inspection of layered material challenges

In this step, the selected technologies were tested at lab-scale on simple specimens, made of $AlSi_{10}Mg$ and manufactured by ALM (material considered as the most similar one to AlSiSc, because at this stage the final material was not yet developed). These specimens met these requirements: they had the same surface quality as the demonstrator; they covered maximum and minimum thicknesses of the demonstrator; and defects were induced to simulate defects expected to arise in-service.

2.2.1. Computer Vision

Regarding CV, three different specimens were manufactured (Table 1).

Table 1. Description of the specimens manufactured to detect defect by CV.

<table>
<tr><th colspan="2">Specimen</th><th colspan="2">Artificial defects</th></tr>
<tr><th>Nº</th><th>Dimension [mm]</th><th>Lay-out (defects induced by EDM)</th><th>Sizes [mm]</th></tr>
<tr><td>1</td><td>100x100x18,3*</td><td rowspan="3">
</td><td rowspan="3">D1 | a=0,5 | 2c=1,5
D2 | a=1,0 | 2c=3,0
D3 | a=2,0 | 2c=6,0
D4 (Nº1,2) | a=5,0 | 2c=15,0
D4 (Nº3) | a=3,0 | 2c=9,0</td></tr>
<tr><td>2</td><td>100x100x16*</td></tr>
<tr><td>3</td><td>100x100x4*</td></tr>
</table>

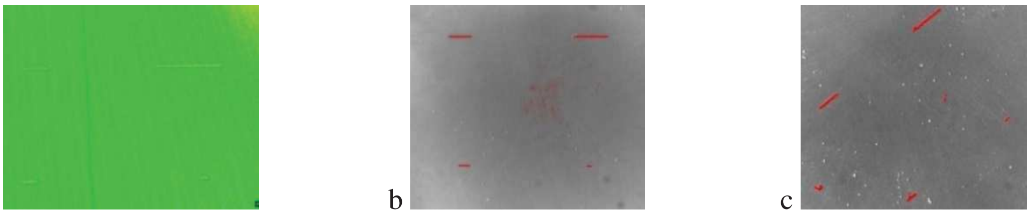
** initially defined thicknesses: 19 and 5mm. Due to ALM, approximate dimensions have been obtained.*

Laser Triangulation was performed with a commercial sensor (Resolution: 0,275mm (XY); 0,055mm (Z)). This resolution was not enough to obtain great contrast to detect notches. Although there are systems with higher resolution, time to inspect the same area could take longer, increasing the time exponentially in case of complex part inspection.

Several tests based on 3D Structured Light were carried out by means of a commercial scanner (Resolution: 0,100mm (XY); 0,035mm (Z)), but the resolution was not enough to detect any defect. However, with David SLS System good results were obtained.

Diffused Dome Light (Domo) diffuses light at all angles. This is the reason why a target with a complex shape can be uniformly lit, eliminating hotspots. Results obtained showed great contrast to detect notches (adding *Halcon* vision library (13) to segment notches from the surface), though areas with spurious artefacts/false positives were also detected.

2D Darkfield was tested by using white and red lights. Better results were obtained with white light illumination, but both techniques showed good results. Irrelevant artefacts on the surface were detected and posterior image processing algorithm need to be used.



a b c

Figure 3. a) Structured Light, b) Domo (+ Halcon), c) Darkfield (white illumination + filter) **Laser Triangulation images are not added due to negative results obtained**

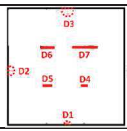
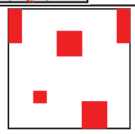
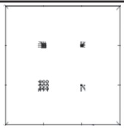
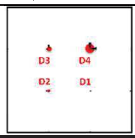
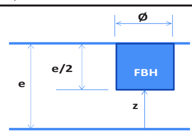
2.2.2. Thermography

Thermography was tested by using 4 different specimens. In that case, internal defects were induced, ones simulated by both Flat Bottom Holes (FBH) and others inducing them during the manufacturing process (Table 2).

The samples were inspected by active IRT (FLIR SC5000). 3 different stimulation approaches were used: continuous optical, pulsed optical and inductive, using a halogen lamp (1KW), a flash lamp (6KJ) and induction coils (15A-10KW), respectively.

Thermography showed no good response to detect internal cracks (Figure 4). Many indications were detected over the entire surface of the specimens that did not correspond to real defects. This could be produced due to the specific internal structure of the material, with high levels of porosity and thermal diffusivity. High diffusivity and porosity distribute the heat rapidly over the material, spreading the heat originated in the defects so quickly that it is not possible to detect any defect before dissipating all the heat even with a high-speed camera.

Table 2. Description of the specimens manufactured to detect defect by T.

Specimen		Artificial defects		
Nº	**Dimension [mm]**	**Lay-out**		**Sizes [mm]**
4	100x100x3,3*		*See details of notches in Table 1*	D1/D4 a=0,5 2c=1,5 D2/D5 a=1,0 2c=3,0 D3/D6 a=2,0 2c=6,0 D7 a=3,0 2c=9,0
5, 6	100x100x23* (5) 100x100x23,2*(6)	5) 	6) 	*Defects induced during manufacturing process. 5) lack of fusion 6) pores*
7	100x100x3*			D1 ∅ 0,2 D2 ∅ 0,5 D3 ∅ 1,0 D4 ∅ 2,0

** initially defined thicknesses: 24 and 5mm. Due to ALM, approximate dimensions have been obtained.*

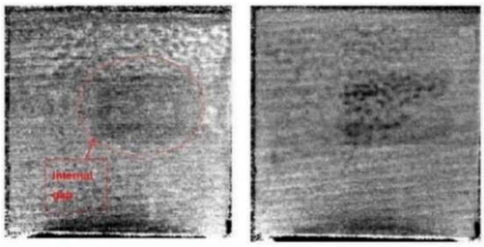


Figure 4. Thermography results corresponding to pulse optical simulation.

2.2.3. Ultrasound

US was tested by using 9 specimens (1, 4, 5, 6, 7) and 4 more (Table 3). Some of them were used to check both acoustic properties (attenuation and sound velocity) and to study the effect of the surface quality; and the rest, to see the capability to detect internal defects.

Table 3. Description of the specimens manufactured to detect defect by US.

Specimen		Artificial defects	Surface quality
Nº	**Dimension [mm]**		
8	100x100x18,2*	*See Table 2, Nº 7*	-
9, 10	50x50x19* (9) 50x50x4,4* (10)	Defect free	Polished surface (Ra<3µm)
11	50x50x18,3*	Defect free	Corundum blasting shot peening

** initially defined thicknesses: 19 and 5mm. Due to ALM, approximate dimensions have been obtained.*

Single element pulse-eco testing was performed by using contact transducers. Straight angle transducers in the range of 2,25–20MHz were used and wedges of 45º and delay lines were also employed. A wide range of frequencies was tested considering the common frequencies used in the bibliography, the grain size and the shape and location of defects. Phased Array (PA) transducers were also considered, but due to their complexity, their use was studied in the next screening, after confirming the positive results of US.

Regarding sound velocity, higher values than steel or Al were obtained (C_L=6581m/s, C_S=3271m/s). Acoustic attenuation tests showed low values for all frequencies, obtaining higher values as frequency increased. Attenuation derived from the surface quality showed huge reduction of echo amplitudes, which was higher as frequency increased (6 to 60 times smaller). The effect of the grain size was tested measuring signal-to-noise ratio, but the results were not significant.

In terms of defect detection, best frequencies were between 10-20MHz. All notches were detected and all FBH except the smaller ones (D1, D2, Table 2, 7). As a negative point, internal defects close to the surface were hardly detected. In Figure 5 can be seen that echoes from small defects and defects near surface are smaller than the bigger ones.

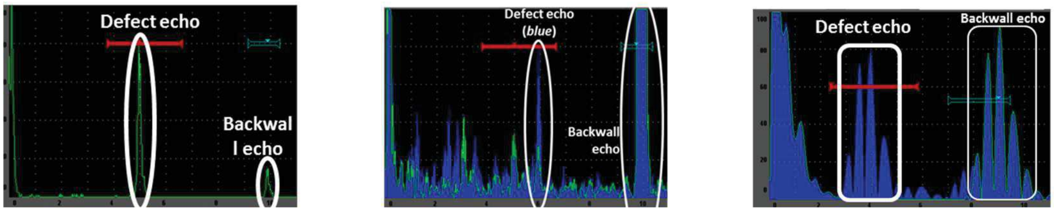


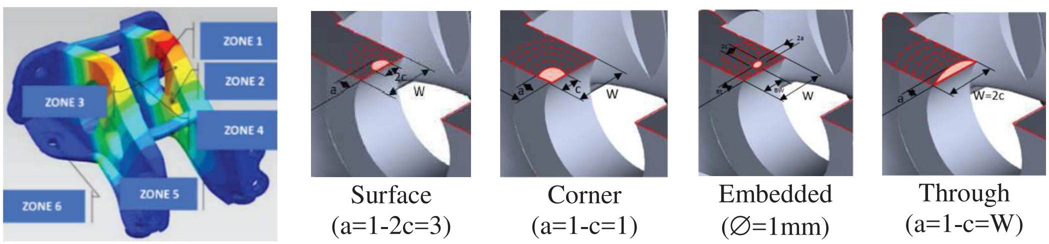
Figure 5. Signals obtained in: (Left) Nº7, D3. (Centre) Nº7, D1. (Right) Nº4, D3.

Thanks to these tests the technologies were evaluated in 3 aspects: the influence of the internal structure of the material; the influence of the surface quality; and the detectability of certain expected type and size of defects. Apart from these tests, other aspects were also considered, such as the accessibility and the maturity level. These last considerations allowed to eliminate some CV technologies, like Terahertz and Deflectometry because of its expensiveness and the huge size of the transducers, respectively. Regarding US, EMAT was discarded due to large size of transducers and Laser US because its limitations on penetration capacity, size of the equipment and expensiveness.

2.3. 3rd screening: lab-scale testing on complex reference specimens. 1st approximation to accessibility challenge

In that screening the selected technologies were tested in complex shaped specimens, in which some of them, artificial defects were induced. The type and shape of the specimens were selected according to the results of the fatigue life prediction study.

This analysis, whose main objective is to establish the expected fatigue life, is based on identifying points where the probability of developing fatigue failures is maximum ("hot spots"). The categorization of the different zones is carried out based on the stress ranges derived from the external efforts, the probability of developing damages associated with corrosion and fretting processes and the NDT crack size threshold. Considering that fatigue cracks propagate according to an exponential law, it is crucial to develop an NDT system with a low damage size threshold to assure a long fatigue life. As a result, critical zones were identified, and four different crack types were considered: surface, corner, through and embedded (in Figure 6 only defects regarding one critical zone are shown but the shape and the sizes are the same in all critical zones). According to these data, complex shaped specimens were defined, and defects were artificially induced (Figure 7). Depending on the defect type and its location, one of two technologies (CV or US) was assigned to inspect each defect. Through crack were not considered because if surface cracks are detected, through cracks will be also detected due to their bigger size.



Surface (a=1-2c=3) | Corner (a=1-c=1) | Embedded (∅=1mm) | Through (a=1-c=W)

Figure 6. Critical zones and shape and dimensions (mm) of each type of defect

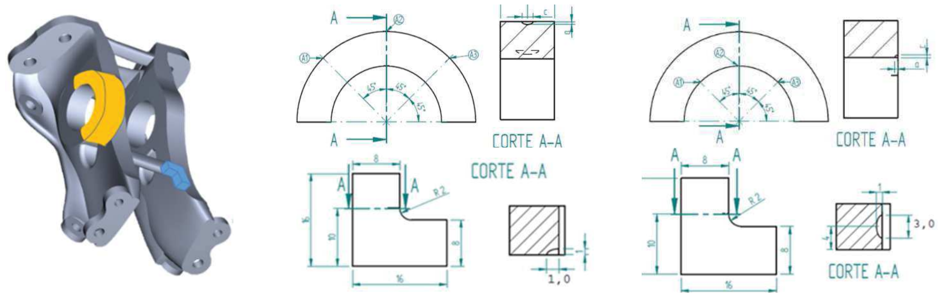


Figure 7. Description of the defects manufactured on complex specimens

2.3.1. Computer Vision

Most surface and corner cracks were able to detect with CV. Laser Triangulation based 3D Scanner, Domo and Darkfield were tested. As a result, Domo and Darkfield were the most suitable technologies. Laser Triangulation based 3D Scanner was not able to inspect cracks (Figure 8).

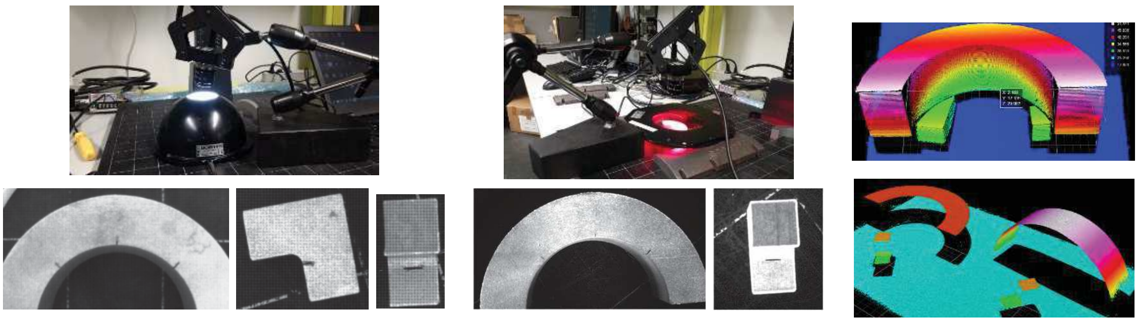


Figure 8. Images obtained with: (Left) Domo (centre) Darkfield (left) Laser Triangulation based 3D vision system

2.3.2. Ultrasound

The inspection with US was not performed in these specimens, because there were not representative due to the complexity of the final demonstrator, as it is shown in Figure 9, where the Inspection Areas (IA) regarding critical zones (Figure 6) are highlighted.

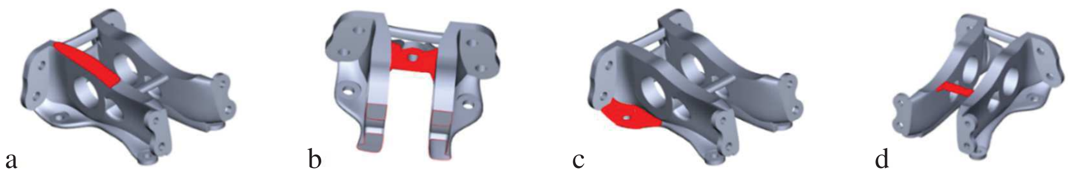
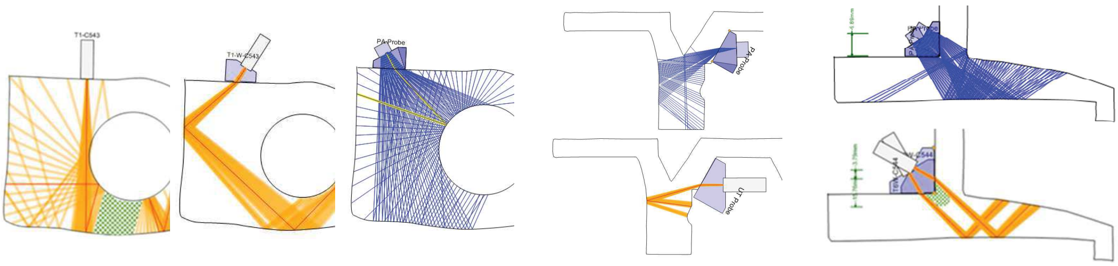


Figure 9. IA regarding zones: a) Z1, Z2 and Z3. b) Z4, c) Z6 and d) Z5

To avoid the manufacturing of more complex specimens, simulations with Beamtool 9© were done (Figure 10), to simulate the performance of the transducers and to identify non-inspectable areas (to define latter, the artificial defects on the entire demonstrator).



a) IA Z1 b) IA Z4 c) IA Z5

Figure 10. Results from simulations identifying non-inspectable areas (in green).

In conclusion, PA transducers seems to offer the best ultrasonic coverage in all zones, but angular single beam transducers are suitable for almost all the zones. Regarding straight angle transducers, more limitations were found. (Table 4)

Table 4. Summary of the usability of each type of transducer

Transducers	Critical zones					
	Z1	Z2	Z3	Z4	Z5	Z6
Straight angle-single element	R	R	R	NO*	NO	NO
Angular single element	OK	OK	OK	OK	NO	OK
PA – 0º / Wedge	R/OK	R/OK	R/OK	NO/OK	NO/OK	NO/OK

**Except one, which works properly; R: Regular (some non-inspected areas)*

The objectives of these tests were, firstly to evaluate the coverage zone of the selected technologies in the areas with most complex geometry, the accessibility, and to evaluate the feasibility to detect the critical defects.

In addition, as soon as the final material (AlSiSc) was available, simple shaped specimens were manufactured and acoustic properties of these specimens were measured (section 2.2.3.) to check if the change of the material required significant changes in inspection strategies. In terms of sound velocity, the obtained results were similar to $AlSi_{10}Mg$ (C_L=6448m/s-C_S=3420m/s). Acoustic attenuation, however, seemed to be lower, specially at high frequencies. In this case, the effect of the grain size was also non-significant. In summary, two materials showed similar acoustic behaviour, that indicates that the results obtained with $AlSi_{10}Mg$ can extrapolate to AlSiSc.

2.4. 4th screening: lab-scale testing on complex demonstrator. Last approximation to accessibility challenge

As a last screening, a study of the potential coverage of the different methods in the most critical areas of the whole demonstrator made of $AlSi_{10}Mg$ was started. By means of a 3D printer the other elements surrounding the bracket have been simulated and the complete layout has been built because at this point it is not enough with the feasibility of the solution for cracks detection, but also accessibility issues are key questions. The project is going to finish at the end of 2019, so tasks regarding this screening have been started but not finished. In this section, preliminary results are presented.

2.4.1. Computer Vision

Some cracks have been inferred in the available bracket for testing purposes. Preliminary tests have been performed over the bracket to check accessibility and inspection feasibility. First impressions show difficulty in getting some parts of it, mainly due to small piece dimensions and design complexity.

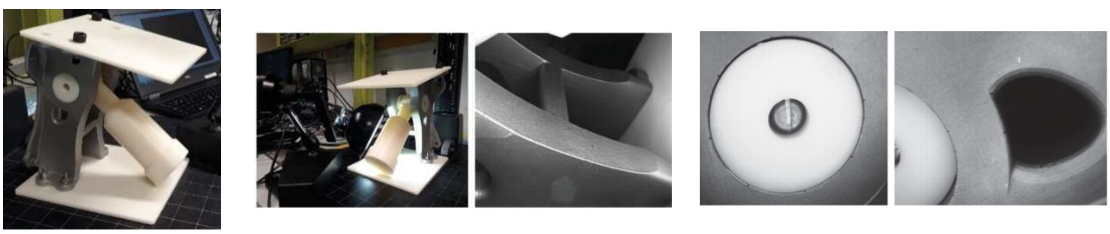


Figure 11. Simulation of the layout and some shots of cracks detected with

Once the best accessing inspection points have been determined, new exhaustive tests need to be performed to check CV technologies feasibility to determine defects from them.

2.4.2. Ultrasound

Considering the information from the simulations, the location and size of the artificial defects on the final demonstrator was established. The objectives of these defects were to cover all the critical zones and to simulate the smallest defects on them (Figure 12). These defects will be induced on the demonstrator and final tests will be performed.

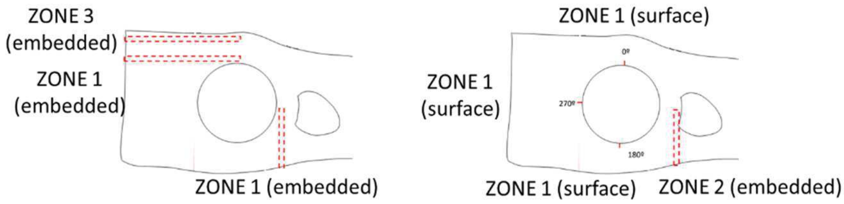


Figure 12. Design of the defect to perform US inspection

3. Results

The methodology followed allowed to select the most potential applicable NDT methods, starting from six technologies and ending up focusing on two main ones. In next diagram it is summarized the stages of the followed methodology, parameters used to perform the screening of NDT technologies and main tasks performed on each.

	1st Screening	2nd Screening Surface quality and internal inspection of material challenges	3rd Screening 1st approximation to accessibility challenge	4th Screening Last approximation to accessibility challenge
NDT Technologies	• US based technologies • X-ray based tomography • Eddy current • Dye penetrant • CV based technologies • Thermography	• US based technologies • CV based technologies • Thermography	• US based technologies • CV based technologies	• US based technologies • CV based technologies
Screening parameters	• Physical properties of ALM parts • SoA of NDT methods for additive manufactured parts • Current NDT methods to inspect similar parts	• Influence of Surface quality • Influence of internal structure • Detectability of different type and size of defects (defects generated in-service)	• Detectability of different defects in critical areas • Accessibility • Evaluation of the influence of the new material	• Accessibility and coverage zones.
Performed tasks	• Study of information collected in screening parameters	• Design & Manufacturing (D&M) of simple shaped samples • Defect definition & induction • Lab-tests	• Identification of critical areas • Critical defects definition • D&M of complex shaped samples • Lab-tests	• Final demonstrator manufacturing • Lab tests about the coverage in the complex parts by the NDT methods.
Results	• To avoid 3 NDT technologies	• US: setting parameters • CV: avoid thermography and structured light	• Influence of the new material • US: to narrow down parameters and transducers • CV: 3D laser triangulation and 2D darkfield are promising techniques	• Selection of most suitable NDT technologies to address the in-service inspection of the whole complex parts.

Figure 13. Summary of the followed methodology and results obtained

Finally, a combination of US and CV based technologies was founded as the most suitable strategy to in-service inspection of these part, although specific equipment/technique for each technology is not still determined (to be established and selected during the execution of the 4th screening). CV techniques will provide information of surface cracks whereas US will allow to detect internal defects.

Regarding CV technologies, final conclusions over complex specimens are: 1) Cracks detection is feasible with Darkfield and Domo; 2) Domo illumination system is preferred; 3) 3D vision system does not provide good results. The width of the crack does not allow the correct detection of the crack. Preliminary conclusions over brackets are that accessibility makes impossible the location of some cracks, mainly with Darkfield and 3D vision system technologies. On contrary, Domo seems feasible (Small equipment in a motorize arm could access to almost all cracks).

In terms of US inspection, PA transducers seems to be the most suitable ones, since the complex geometry of the transducer do not allow to use common ultrasonic transducers, or their use is limited. Next experiments on the demonstrator will show the most adequate transducers as well as may be possible to identify some un-inspectable defects, highlighting the limitations to perform in-service inspections.

4. Conclusions

To face the in-service inspection of bionic parts manufactured by ALM, it is necessary to consider aspects like the internal structure of this new material (adding the surface quality), the accessibility and the expected unknown defects.

The internal structure will define the technologies to inspect internal defects, such as the acoustic performance to define US parameters as well as the applicability of thermography (discarded due to the high thermal diffusivity). The surface quality will be a constraint not also for internal defect detection, also for CV based technologies. The accessibility will be evaluated in terms of the size of the equipment required, because in-service inspection requires that the sample is attached to the structure. All these considerations will be limited by the critical areas identified in the fatigue life analysis, which also will allow to know the type and size of defects to be detected.

The methodology proposed in this work considers all these challenges and allow to perform a screening of NDT technologies following certain steps which are useful to select potential technologies in an efficient manner, from theoretical analysis over simple lab-tests and simulations to complex lab-experiments. In the presented use case, 6 initial technologies have been reduced to 2, and therefore only these two technologies were tested in the final demonstrator, simplifying the tests and saving time testing unnecessary technologies.

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