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Repair & maintenance by Metal Additive Manufacturing process on Titanium alloy parts

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Abstract. The CRO² project* deals with both the aircrafts' parts repair & maintenance and the Additive Manufacturing by metal powder Directed Energy Deposition **.

Repairing parts in the aerospace industry is a potential application for additive manufacturing technologies. It's thus possible to reduce operating losses and to avoid waste of costly and strategic raw materials. CRO2 proposes a pre-industrial development to rebuild lost shapes and functions of Ti64 alloys structures as example in air bled piping. Laser Metal Deposition (DED) process was used for Ti64 parts manufacturing. Tensile and fatigue tests were performed on several samples to characterize the AM material. The mechanical properties of the tested samples are comparable to those of the laminate Ti64 and their microstructure is typical of additive manufacturing. The reliability of the proposed technique, compared to welding repairs' process, has been successfully demonstrated using aircraft environmental qualification tests at high temperature and pressure carried out on thin representative pipings.

(*) CRO²: *Cost Repair Overhaul Optimization*

(**) DED AM: *Directed Energy Deposition Additive Manufacturing*

1. Introduction

Titanium alloys are today more and more employed for structural parts in aerospace applications due to their good mechanical properties on severe mechanical and thermal environments, and because they are well compatible with Carbon Fibre Reinforced Plastic structures largely used on new aircrafts' programs.

In aeronautical domain, repairs are a major issue to improve the current way of manufacturing, to avoid waste of costly and strategic raw materials and to reduce operation losses. Nowadays most of repairs are made by welding or complete replacement of the lost functions or whole parts. These methods have a high energetic impact, weaken locally the parts, make them heavier and modify the paths of mechanical forces. Some studies have been already performed on repair made by Ti64 Additive Manufacturing [1] but only on grooves not on a complete function. The study of *Graf and al.* does not completely evaluate the mechanical properties of the deposited materials. They did not validate the



repair by environmental tests. The *CRO*^{2*} project aims to develop a pre-industrial method to rebuild lost shapes and functions by using DED AM^{**}.

Additive manufacturing is developing since few decades to build complex shape structures, rapid prototyping or repair. The DED^{**} process delivered the metal powder by a nozzle to the molten pool generated beneath the laser scanning beam. This process uses less energy than welding, which results in a low mechanical distortion and a small heat affected zone [2].

The *CRO*² project focuses on low critical structures in Ti64 titanium alloy as air bled piping. Firstly, the deposited metal has been characterized by static and fatigue mechanical tests and metallurgical tests. Secondly, with the proper process' parameters, demonstrators have been realized on thin bled piping (0.8 mm thick). Finally, aircraft environmental qualification tests have been performed on these technological demonstrators to validate the *CRO*² solution robustness.

(*) *CRO*²: *Cost Repair Overhaul Optimization*

(**) *DED AM: Directed Energy Deposition Additive Manufacturing*

2. Materials and methods

2.1. Samples

To characterise the deposited matter by DED process, mechanical and metallurgical samples have been made. These samples have been extracted from huge walls built by DED process with OPT'ALM's deposition machine. The device is compound of a DED deposition nozzle on a 5-axis CNC machine and a 2kW laser fibre source. The powder is carried to the nozzle through Argon gas flow. The powder flow is melted by the laser on the deposition surface. The deposited weld is around 1.0 mm thick and 0.5 mm high. Its size depends on the main process parameters: the laser power (P), the displacement speed of the nozzle (V), the powder flow rate (D).

The optimal parameters have been defined by a TAGUCHI experimental test plan. The main process parameters chosen for this study are: laser power 700W, deposition speed 1700 mm/min and material flow 5 g/min. The construction is performed in an inert Argon atmosphere (O₂ content less than 40 ppm). This atmosphere helps to protect Ti64 powder and parts from the oxidation at high temperature.

Tests and analyses were also carried out after heat treatment: stress relaxation (720 ° C for 2 h) and HIP (920 ° C, 1020 bar for 2 h).

The microstructure has been observed on samples after polishing by grinding, OCS suspension finishing and etching with Kroll agent. The samples have been observed with an optical microscope MA200L and by EBSD-SEM.

The tensile tests were carried out using a 3R SYNTECH 1510 machine. Half of the samples have been surface-machined. As-built and surface-machined samples have been extracted in transverse and longitudinal directions. The samples have been designed according to standard ISO 6892-1 method A (170 mm long; 13 mm width; 4 mm thick).

Fatigue tests have been performed using a SCHENCK Hydropuls PS3007B machine. All samples have been surface-machined and extracted in longitudinal direction. The samples have been designed according to standard NF-EN 60712-1, annex B, method (Kt=1,0 130 mm long, 10 mm large and 3 mm thick). The samples were stressed at 60 to 95% of the yield strength (480 to 760 MPa). Stress-controlled HCF tests were carried out at room temperature at a strain rate of 0.025/sec and a load ratio of R = 0.1. Sinusoidal cycles were applied at a frequency of 10 Hz.

2.2. Bled piping demonstrators

Two technological demonstrators of Titanium alloy air bled piping have been built with the same manufacturing parameters used for mechanical tests. The DED AM built part is a cylinder with a water tower shape (Figure 1). It has been made on a thin (0.8 mm) tube in T40 titanium alloy.

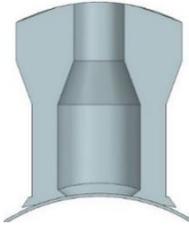


Figure 1. CAD cross section view of the reconstructed water tower shape on a thin tube

Several construction tests were performed to obtain any pores at the junction between DED added area and the substrate, which can fragilize the structure and generate leakages during environmental tests (Table 1). Therefore, the building strategy was tuned by enlarging the bottom interface and reducing the thickness of a weld bead. The porosity has been controlled by X-ray microtomography with a EasyTom 130 Micro CT Scanners.

Table 1. Conditions of environmental tests for the demonstrators

Test	Temperature (°C)	Pressure (bars/Psi)	Time stop (min)
1	20	3.5 / 51	5
2	20	40.4 / 586	5
3	281	14.8 / 214	5

The demonstrators have been tested in pressure and temperature on an aeraulic test bench in aeronautic environmental qualification conditions (Table 1). Collars have been added by DED AM to ensure a good sealing with the test device (Figure 2).



Figure 2. Piping demonstrator with its pressure/temperature probe mounted in the aeraulic test bench.

3. Results and discussion

3.1. Samples

The microstructure observed on Ti64 samples is fine and lamellar (Figure 3 a-b). The primary β grains form long columns observed on macrographs. In higher magnification, the α and α' needles phases are detected in β grains. This microstructure is typical of additive manufacturing [3]. Indeed, the high difference of temperatures between the melting area and the environment leads to important cooling rate. It can be compared to a quenching. Moreover, the consecutive deposited layers generate thermic cycles and a growth of grains according to the heat flows: from the substrate to the top and the external surface.

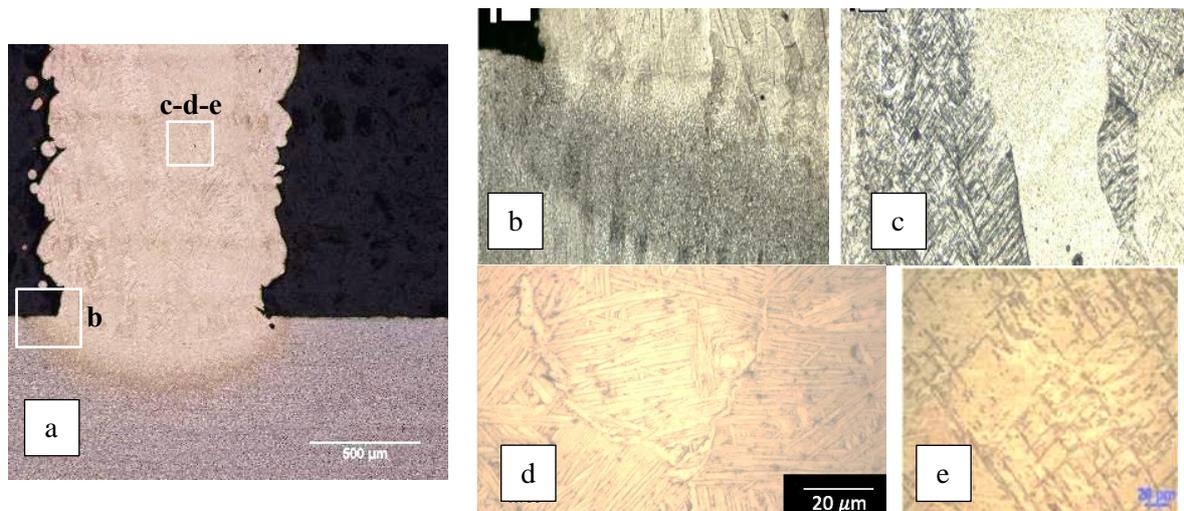


Figure 3. Microscopic observations at different magnifications. (a) large view of the DED sample (top) on its laminated substrate (bottom), mag. x20; (b) dilution area between the substrate and the first DED layers, mag. x50; (c) different primary β grains (black) with α needles (white), mag. x200; (d) α needles, mag. x1000; (e) microstructure obtained by DMD for comparison [4].

The grain size and shape depend on the deposition strategy because the primary grains β are oriented along the heat flows. For cylindrical shapes such as tubes, there are thermal radiation effects and heat trap phenomena between the internal walls. They slow down the cooling of the part and the heat flows are radial with a radially grains' growth and coarser grains. On straight line shapes such as walls, there is no thermal radiation effects, nor heat concentration by thermal traps. The cooling is therefore faster, the grains are finer and oriented mainly towards the top of the construction.

The EBSD analyses highlight the primary β grains and their growth [3]. Primary β grains are large and columnar. Their growth takes place along heat flows. On Figure 4, samples come from a wall and the heat fluxes are mainly along z (towards the top of the sample on DED area). This grain growth is typical and specific to additive manufacturing processes, through their construction layer by layer and repeated thermal cycles. The α and β grains' orientation is homogeneous within a primary β grain (Figure 4). The orientation and growth grains are different from that of the substrate, where the grains are smaller, equiaxed with random orientation. The specific orientation of the additive manufactured grains can generate anisotropy in mechanical properties such as elongation at break.

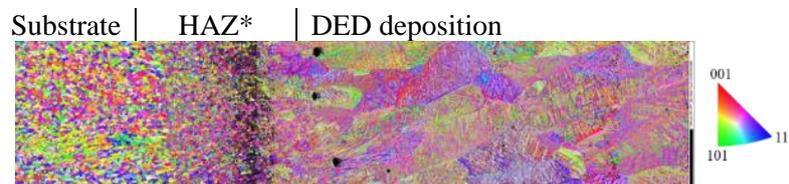


Figure 4. Orientation of grain observed by EBSD analysis on DED sample and its substrate, normal to construction plane in IPF.

(*):HAZ: Heat Affected Zone

The EBSD image shows some black dots which are pores (Figure 4). These pores are small and irregular. They are located at the bottom of the sample, close to the substrate where the heat exchanges are different from the rest of the part. The majority of the energy provided by the DED process is dissipated in the substrate by thermal conduction while on the rest construction, this energy is dissipated by thermal conduction and convection. The pores should therefore not influence the mechanical properties of the DED part (premature or brittle rupture, drastic reduction in elongation).

The material is not fully isotropic. The anisotropy is strongly measured on elongation, with a difference of 40% between the longitudinal and transverse direction (Table 2). The mechanical strength is higher in the longitudinal direction, parallel to the deposited weld beads. The stress in this direction is perpendicular to the primary grains β , which are oriented to the top of the construction. Like composite materials, it is more difficult to break samples when the force is parallel to the DED weld beads rather than perpendicular to them.

As-built specimens have a roughness $R_a = 24 \mu\text{m}$ which favours the cracks propagation. The CNC machining improves slightly (around 5% on the UTS) the results by reducing roughness and it has no impact on elongation. The elongation is mainly linked to the state of matter: its porosity rate, its internal defects and above all its microstructure (phases present, crystallographic orientation, growth and grain shapes).

After relaxation heat treatment, the microstructure of samples is not changed since the temperature is lower than the β -transus. The grains are always fine and acicular. After High Isostatic Pressing (HIP), the grains on DED area are coarser and more equiaxed, with in particular an enlargement of the α grains, and a more lamellar structure. At the junction between the weld beads, strings of grains α are observed.

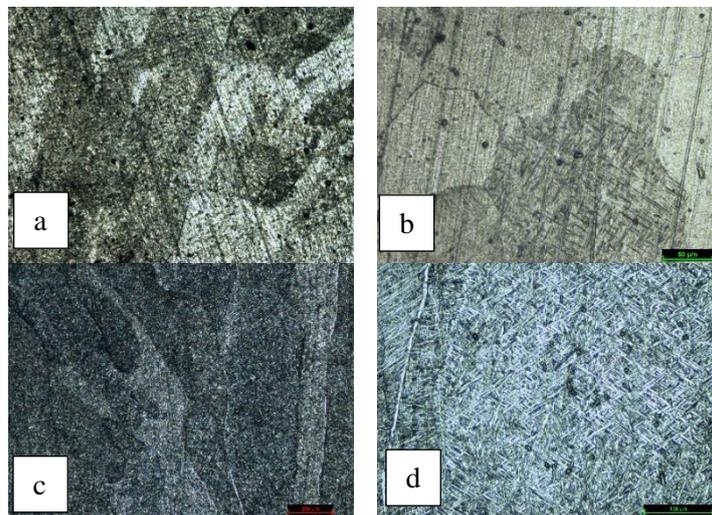


Figure 5. Microscopic observations at different magnifications. (a) After relaxation view of DED different primary β grains (black) with α needles (white), mag. x50; (b) After relaxation view of DED different primary β grains (black) with α needles (white), mag. x200; (c) After HIP view of DED different primary β grains (black) with α slats (white), mag. x50; (d) After HIP view of DED different primary β grains (black) with α slats (white), mag. x200.

By comparison with others technology such as SMD [5], EBM or casting [4], DED process allows to reach stronger but less ductile metal. The results are coherent with the observed microstructure [6]. The finer the grains are, the stronger the metal is. Lamellar microstructure is characteristics of low ductility and good crack growth resistance.

On longitudinal CNC machined samples, strengths' values without thermal treatments are around 15% lower than those coming from rolling but greater than those coming from casting. The variations in mechanical strength are consistent with the microstructures observed after heat treatment. The low variation in mechanical properties after stress relaxation shows that the DED process induced low stresses. After HIP the mechanical properties are therefore impacted by an increase in elongation and a decrease in strength, to be close to wrought Ti64 values. The HIP treatment improves fatigue behaviour of the DED part but it influences the substrate by decreasing its mechanical properties.

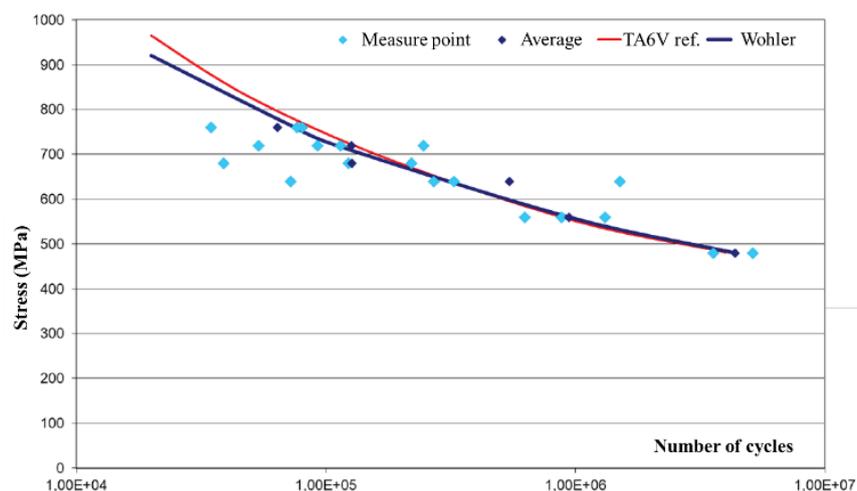
Table 2. Mechanical properties obtained on DED samples and comparison with other manufacturing processes

		UTS (MPa)	YS (MPa)	E (GPa)	A (%)	Reference
As built	<i>Longitudinal</i>	991	899	108	10	This work
	<i>Transverse</i>	945	850	108	5.9	This work
Machined	<i>Longitudinal</i>	1049	915	113	10	This work
	<i>Longitudinal</i>	930	830	113	13*	with HIP
	<i>Longitudinal</i>	1015	955	113	9	stress release
	<i>Transverse</i>	959	830		5.9	This work
Rolling (quenching + hardening)		1150	1050	110		[4]
Casting		900	800	110	10	[4]
SMD (wire)		929 – 1014	/	---	9 – 21	[5]
EBM (electron)		1020	920	---	11	[4]

About the stiffness of the material, the Young modulus values are very close whatever the DED samples and whatever the construction direction. They are similar to those coming from other manufacturing process (casting, SLM).

The fatigue results obtained on Ti64 samples allowed to plot WÖHLER S-N curve which correctly fits with literature (Figure 6). 21 samples have been tested and the unlimited lifespan of the DED Ti64 is reached near 60% of the maximum load (around 480 MPa). At this load level a sample was unbroken at 4.10^{+6} cycles and another one at $5.1.10^{+6}$ cycles (stopped after 7 days).

Despite a small number of samples, the first fatigue test results tend to show an infinite lifespan with a load of 60% of the ultimate strength. The behaviour of Ti64 obtained by DED additive manufacturing is close to the laminated one. The parts produced by DED are able to work in fatigue environments. The sample CNC machining process has helped to obtain better results by eliminating surface roughness and most of the residual strains on surface. The low internal pore rate and the microstructure are also other significant contributing factors to improve fatigue performance.



3.2. Bled piping demonstrators

Two pressure/temperature probe support demonstrators were built for the pressurization tests (Figure 7). The shape of the probe support is that of a “water tower”. It ensures all the functions of the support, good grip and good sealing at the junction with the substrate tube. In this application, the surface roughness has not significant impact on mechanical strength under static pressure. The heat affected zone is small and there is no deformation of the tube at the base of the constructions.

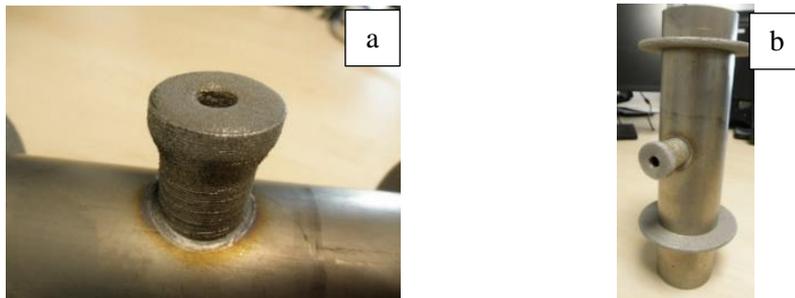


Figure 7. Piping demonstrator: (a) the As-built shape of the probe support on thin tube; (b) complete demonstrator with collars at the extremities to ensure the sealing with the test bench.

The microtomography observations made on the DED demonstrators show pores at the bottom of the “water tower shape”, near the junction between DED area and the substrate on the first deposited layers. These pores appear between two adjacent weld beads. The weld beads are not perfectly cylindrical and have an oval shape. During the deposition, it must have an overlap between two adjacent beads to allow homogeneous and relatively flat layer to be obtained. If this coverage is too great, there is a surplus of material and therefore a "bump". If it is too weak, this creates a "hollow" and therefore a pore. The CNC machining step and the induced cutting forces favoured the opening of these pores. They damage the material and they caused a leakage during the pressurisation test on the first demonstrator.

Then, the DED strategy was changed to reduce the overlap between two adjacent beads, which made it possible to reduce the pores (Figure 8). In addition, the CNC machining operations have been adapted to locally reduce mechanical forces.

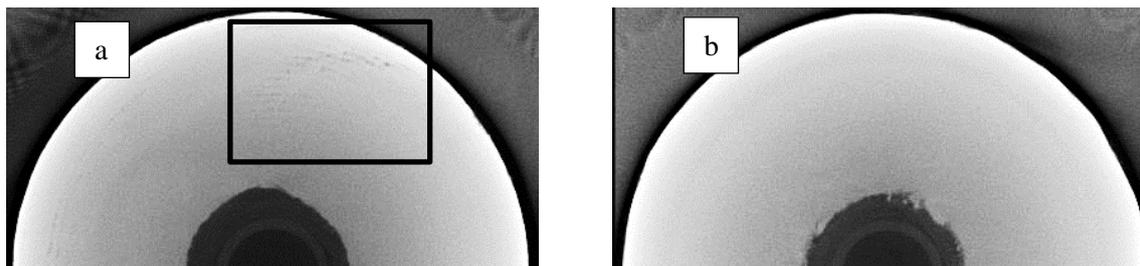


Figure 8. Microtomography images of probe support cross sections (water tower shape) (a) strategy with pores (darker elements on the square); (b) changed strategy without pores.

Three test conditions have been applied to two new demonstrators realized with the second DED strategy (Table 1 and Figure 9). Some overloads compared to the specification appeared. They are due to thermodynamical effects on test bench: greater duration at the stop, slightly higher pressure and temperature at the beginning of stops and during the pressure drops. Any leakages and pull-out were observed after tests. The qualification campaign for both demonstrators was successful.

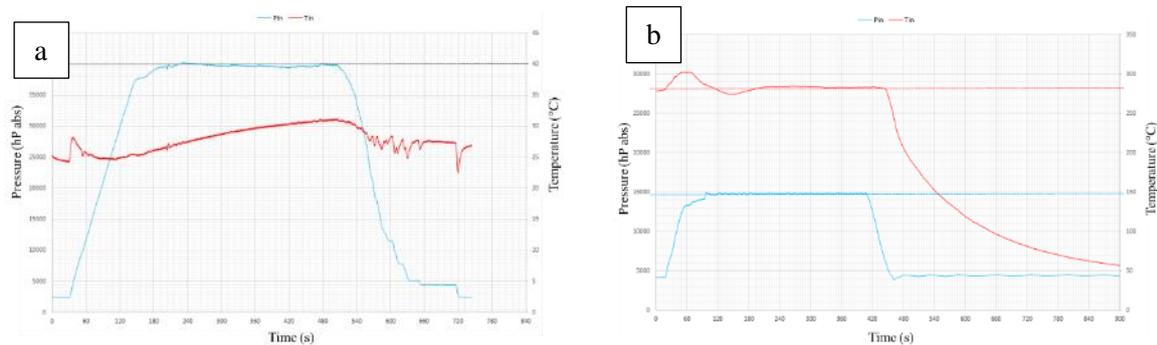


Figure 9. Applied pressure (blue) and applied temperature (red) to demonstrators during (a) the pressurisation test 2; (b) and the pressurisation test 3.

4. Conclusions

In this collaborative project with the CRITT M&C, OPT'ALM has demonstrated its ability to master DED process parameters for Ti64 alloy repairs and manufacturing.

Manufacturing powder suppliers have been selected and evaluated according to aeronautic standards to insure the raw material traceability. The created and deposited alloy by DED has been characterised in mechanical tests' campaign and microstructural analyses.

The results enhanced a more resistant matter with less elongation. It is coherent with the fine martensitic microstructure observed on each sample. This microstructure is relative to the quick cooling brought by additive manufacturing processes. The samples are dense and present any pores.

The mechanical results in static and fatigue tests show that the behavior of Ti64 deposited by DED additive manufacturing is close, sometimes even better, than that of conventional Ti64 (rolled, casted). These results must allow mechanical engineers to use safely DED process in design offices.

Repairs on representative structures of thin Titanium alloy air bleed pipes have successfully passed qualification environmental pressure/temperature aircraft tests, which demonstrate that DED additive manufacturing repair is as strong as the welded solution.

OPT'ALM and the CRITT M&C are ready to go into depth for preparing static and fatigue tests to reach qualification and certification according to the applications.

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