EVALUATION OF EFFICIENCY AND MECHANICAL PROPERTIES OF INCONEL 718 COMPONENTS BUILT BY WIRE AND POWDER LASER MATERIAL DEPOSITION

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ABSTRACT

Purpose: The purpose of this paper is to evaluate and compare powder and wire Laser Material Deposition (LMD) processes.

Design/methodology/approach: In the present article Inconel 718 tensile test probes were built layer-by-layer using a longitudinal strategy and the quality of the deposited material was characterized for both wire and powder LMD processes. The measured data during the deposition tests has been used for comparing the efficiency of both powder and wire LMD processes. Afterwards, in order to evaluate the mechanical properties of the parts generated by means of both processes, standard tensile tests were carried out. Furthermore, other factors have been evaluated, such as process reliability or presence of residual material after the deposition process.

Findings: Results show a higher efficiency of the wire LMD process and even similar ultimate tensile stress values were reached for both processes, powder LMD parts resulted to have a more brittle nature.

Originality/value: In the present paper a thorough analysis that compares both processes has been carried out. The results obtained will help in the future when choosing between wire and powder LMD. The main points of the wealth of knowledge generated with these research efforts are highlighted herein.

Keywords: Powder, wire, efficiency, mechanical properties, LMD.

Paper type: Research paper

1. Introduction

Laser Material Deposition (LMD) is a process in which material is added to a substrate (Bogue, 2015) and two different configurations have arisen during the last decade: Powder and wire LMD. The process basics are similar for both configurations, since a laser beam is used for melting the substrate and a filler material is added into the melt pool in order to add new material (Barua *et al*., 2014). In the case of wire LMD process the filler material is drawn in wire form, whereas in powder LMD a powder stream is injected into the melt pool.

Both technologies are used basically for repairing damaged zones or the reconstruction of worn parts (Costa and Vilar, 2009). The main advantage of these processes is the high quality of the deposited material structure, valid for the repair of determined zones as well as the manufacture of whole parts, reducing the total machining operations and the amount of removed material (Kaierle *et al*., 2012). Today's most important applications for LMD are the repair and coating of high added value and high precision machine components (Wissenbach, 2011). LMD process is particularly interesting for medium and large high added value parts, where forging or casting sections can be reduced and material may be added as protruding geometries. One of the most relevant cases is the turbine industry, where the buy-to-flight ratio can be reduced from 20-30:1 to 5-1.5:1 levels (Tabernero *et al.*, 2011).

As a laser is used as the heating source, the energy is highly focused on the working area and the treated parts result in minimum HAZ (Heat Affected Zone), low dilution and minimal thermal distortions. Once the LMD process is finished, the resulting surface roughness and dimension accuracy is generally out of the final requirements, so a final machining is needed (Klocke *et al*., 2014). However, compared with the conventional finishing operations from forgings, the amount of material to be removed at this stage is much lower. Therefore, LMD process is considered as a near-net-shape process.

Regarding the filler material delivery system, in powder LMD process metallic powder particles are dragged by an inert gas into a nozzle that focuses the powder stream into the melt pool. The nozzle can be coaxial or lateral taking the laser beam axis as the reference. In the coaxial nozzle case, since powder is distributed coaxially among the laser beam, the LMD process can be applied in any direction (Kaierle *et al.*, 2012). This configuration is the most flexible solution and can be applied to generate any desired geometry.

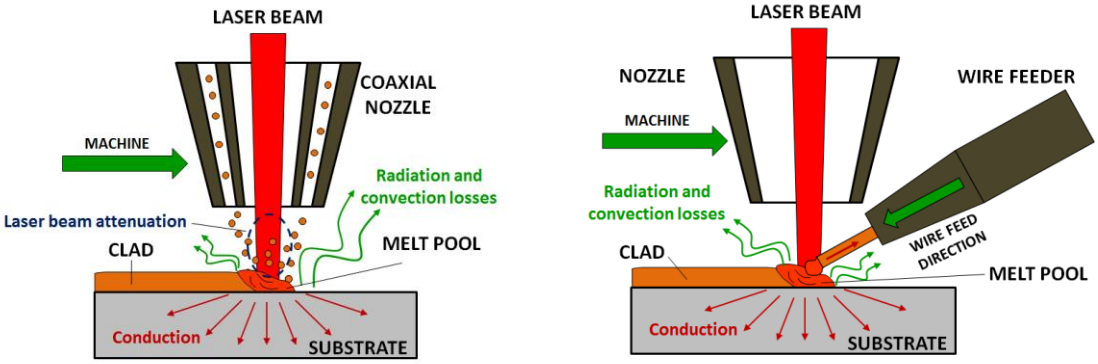
In wire LMD process, the most common configuration is based on a lateral wire feeder, where the incidence angle is a key factor in the process (Mok *et al*, 2008). The application of a lateral feeder limits the process directionality, since material can be only deposited parallel to the wire direction. Thus, this can generate many difficulties for complex repairs or additive manufactured structures where different deposition strategies may be required. This is even more accentuated due to the fact that the wire feeder system must be positioned very close to the processing area to allow an accurate feeding of the wire into the melt pool.

Regarding this point, and with the objective of improving this limitation of the wire LMD, Leyens and Beyer proposed a technique to feed the wire coaxially and melt it using three lateral laser beams, which previously were split from a single incoming beam (Leyens and Beyer, 2014). This system enables the wire LMD process to be omnidirectional. The main disadvantage of this configuration is the geometric limitation due to the size of the laser beam guidance head.

A review of the previously published works shows that most researches are focused on the advantages and disadvantages of using wire or powder. In cases where powder and wire LMD processes are compared, most authors highlight the much lower mass efficiency of powder LMD in comparison with wire LMD. Mass efficiency is defined as the ratio between the trapped material into the melt pool and the total mass of the injected filler material in the same time (Bertsche *et al*., 2007). Some works have measured this efficiency in powder LMD ranging around 30% (Syed *et al*., 2006) whereas in the case of wire LMD almost the 100% of the wire is attached to the base material (Kaierle *et al*., 2012).

Further works mention that using wire as deposition material, involves several advantages including lower cost, higher material efficiency, lower contamination, lower oxidation and fewer defects together with a higher deposition rate (Zhang *et al*., 2013). Conversely, other authors like Toyserkani mention that powder LMD has been demonstrated to be more effective and flexible (Toyserkani, 2005). It also highlights that wire LMD parts have a lower surface quality, low bounding

Figure 1: Schemes of powder and wire LMD processes including the physical phenomena involved.



strength and that porosity, cracks and drop transfer problems may appear.

As it can be seen in the previous paragraph, it is not easy to determine which process is more suitable for industry. Moreover, none of the previously mentioned authors focused their research in the comparison of the mechanical properties of the manufactured parts, nor the real process efficiencies, which are very relevant factors and in addition, offer quantitative information for the process comparison.

Different works have been focused on the analysis of the mechanical properties and microstructures generated in wire and powder LMD processes (Gu *et al.*, 2012). Authors like Zhong, carried out a detailed analysis of the mechanical properties, internal defects and microstructure properties of the Inconel 718 formed by high deposition-rate laser metal deposition (Zhong. *et al.* 2016). Other authors, analysed the structure and hardness of the wire LMD Inconel parts, identifying the different microstructures present in different zones of the substrate and deposited material (Zhang *et al.*, 2013).

Besides, Sun et al. carried out a detailed work of AISI 4340 steel deposited parts with the aim of studying the effects of the stress-relieving treatments on the deposited material structure. In that research, tensile tests were performed in order to evaluate the material mechanical properties (Sun *et al.*, 2015).

Nevertheless, all of them compared the results obtained with those of the base material, what does not help at the time of choosing the correct alternative between wire or powder LMD processes. Therefore, this work is based on building of the same test parts in the same machine using wire and powder LMD processes. A thorough analysis that compared both processes has been carried out: On the one hand, process time, flexibility and efficiency have been analysed. On the other hand, hardness, microstructure, internal defects and mechanical properties of the deposited material have been also evaluated.

Table 1: Compositions of Inconel 718 powder and wire used in the experimental tests.

Element	Composition [wt.%]	
	Powder	Wire
Ni	53	53
Cr	18-20	18.5
Fe	17-19	23.5
Mo	2-4	3
Ti	0.5-1.5	1
Ta	0-5	-
Nb	0-5	-
Al	-	0.5
Others	1	0.5

2. Involved physical phenomena

Powder and Wire LMD processes are based in the same principle: a laser beam is used to melt the substrate, generating a melt pool, and a filler material is added in this area, which is also melted.

From the point of view of the substrate both processes are similar; the surface of the substrate absorbs the laser radiation and this heat is distributed among the substrate by means of conduction, see Figure 1. Both processes use a laser beam as a heat source: In wire LMD usually higher material deposition rates than in powder LMD are obtained, and therefore, the laser power needs to be slightly higher. However, reached maximum temperatures and developed temperature gradients are similar in both cases. The total amount of heat introduced is very low and it is localized in a very small area. Therefore, when the laser beam moves, molten material solidifies almost instantly and cooling rates up to 10^3-10^5K/s are obtained, what leads to the typical dendritic structures (Dinda et al., 2009).

Also, in both processes there are heat losses as a consequence of the reflection, emissivity and convection. However, as the same substrate material is used with an identical surface finish, all these losses can be considered similar.

Nevertheless, there are some relevant differences between powder and wire LMD. In powder LMD, the laser beam is attenuated as a result of the powder cloud generated above the working plane, see Figure 1. As a consequence of this attenuation, powder particles are heated, but the laser power that reaches the surface of the substrate is lower than the programmed. Attenuation values up to the 20% of the original laser power are experimentally obtained in powder LMD process (Tabernero *et al.* 2012).

In wire LMD this phenomenon does not occur, nonetheless, in the case of wire LMD a percentage of the heat introduced to the process is lost through the wire itself due to the conductivity, see Figure 1. This fact is relevant when determining the process parameters. If the laser power is too high, the wire could start melting due to conductivity before it reaches the melt pool and droplets may generate. Consequently, the process becomes unstable and uneven clad geometry is obtained.

When the influence of the process parameters on mass transfer is discussed, usually a higher laser power involves a wider clad (since the melt pool becomes larger), but there are certain limits such as the generation of plasma due to the overheating of the material. Conversely, a higher machine feed rate reduces the amount of energy and material added per substrate surface unit and entails a smaller clad. Nevertheless, the processing parameters vary depending on the material combination and laser configuration, so the process requires an experimental setup in order to find the optimum parameters.

3. Experimental set-up and test procedure

With the aim of comparing both processes (wire and powder LMD) the same geometry was built using the same equipment. For this purpose, a 5 axis CNC machine (Alzmetall GX 1000/5-T-LOB), coupled with a 4,5kw diode laser was used. The machine is prepared for both wire and powder LMD processes, avoiding the possible influence of machine position or kinematic errors during the process. A longitudinal deposition strategy was used in both cases, which was proved to provide the best results for the tensile tests (Tabernero *et al*., 2011). A ZIG strategy was used in wire LMD, because of the directionality of the process, and a ZIGZAG in powder LMD.

The Precitec YC52 cladding head has been used, with a 250mm focus length. At the working plane, the laser spot diameter was 2.1mm and Argon gas was used in both cases as protective and drag gas. The base and filler material for all the tests was Inconel 718. Powder and wire compositions are detailed in Table 1. Powder grain size diameters range between 20 and 53 microns, and a 1mm diameter wire was used for wire LMD tests.

In order to ensure the particle size distribution, a 100-particle sample was taken and their diameters were measured. In Figure 2 can be seen how experimental results fit very precisely the Rosin-Rammler distribution.

The powder was supplied by a conventional rotary powder feeder that allows to feed the process with a constant powder mass flow. Whereas for the wire, the machine has a bobine type feeder used also for TIG welding process.

First of all, the optimum process parameters were determined in single clad tests and then the overlapping parameters were determined. The optimum deposition conditions were defined as those where the clad height was maximized, but without generating plasma due to the material overheating. These parameters are detailed in Table 2, where "*P*" is the laser power, "V_f" is the feed rate of the machine, "f_{wire}" is the wire feed rate and "$\dot{m}_{powder}$" is the powder feed rate.

Figure 2: Inconel 718 particle size distribution and a SEM image.

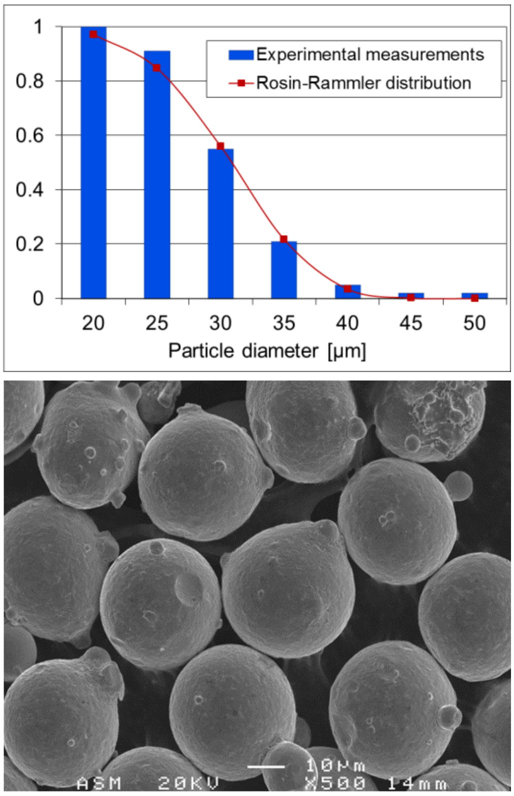
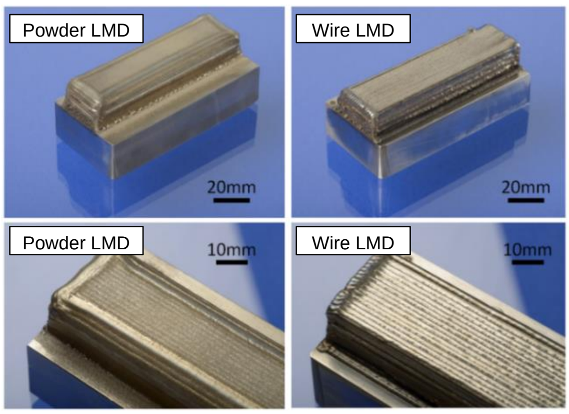


Table 2: Process parameters used for powder and wire LMD.

	Powder	Wire
P [W]	850	700
V_f [mm/min]	500	500
Ovelap distance [mm]	1.5	1.5
Layer high [mm]	0.4	0.85
f_{wire} [mm/min]	-	825
$\dot{m}_{powder}$ [g/min]	4	-

Figure 3: Final shape of the powder (left) and wire (right) parts.



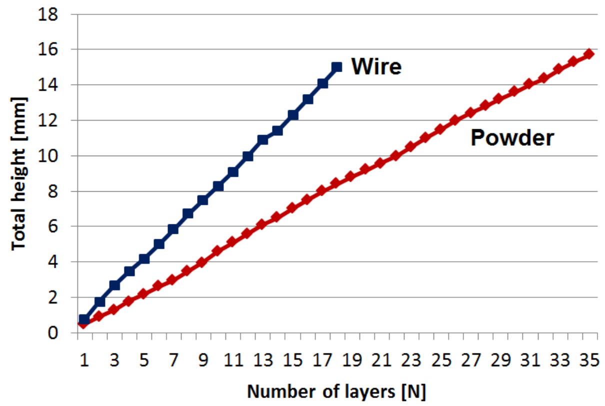
Once the deposition process was finished, a precipitation hardening heat treatment was carried out in order to improve the mechanical properties of the parts and enhance their hardness. This heat treatment is commonly used for Inconel 718 parts and includes a solution treatment at 980ºC (for 1h) followed by an air cooling and afterwards a two-step ageing treatment: 720ºC (for 8h) + 55ºC/h furnace cooling until 620ºC + 620ºC (for 8h) + air cooling. In Figure 3 the finished parts built by powder and wire LMD and a detail of the surface finish are shown.

4. Experimental results comparison

As expected, both processes resulted to be capable of building the desired test parts. Wire LMD presents a higher material deposition rate and therefore the number of layers required to generate the desired geometry was reduced substantially, see Figure 4.

A relatively uniform height grow was obtained in both cases. The clad height increase was measured after every layer deposition, resulting in low oscillations in the height increase, what enables an automatic programming of the process. Experimental results show that the deposition rate of the wire LMD is about twice as the deposition rate of the powder LMD. The deposition rate for the powder LMD could be increased with a higher powder flux, but with the used equipment could not be assured a constant powder flux and the clad height would became unstable.

Figure 4: Height reached with the increasing number of layers.



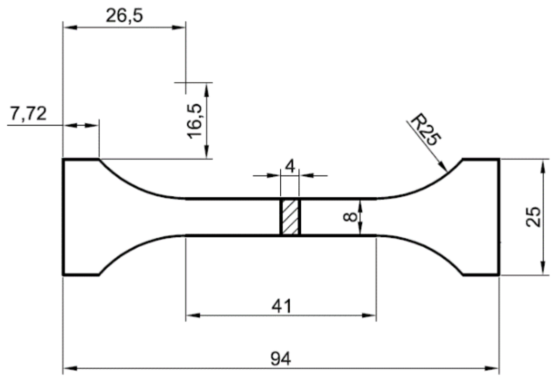
Since the wire needs to be introduced into the melt pool, there is a mechanical contact between the wire and the substrate. However, in powder LMD process once the powder exits the nozzle, it is projected to the melt pool and there is not contact between the LMD system and the substrate. In other words, there is mechanical independence between the substrate and the feeding system. Furthermore, powder LMD process is partially auto-regulated, because if the powder stream is slightly out of focus, the material deposition is reduced but the process continues. However, in the case of wire LMD, if the wire contacts the surface of the base material outside the melt-pool, the process becomes unstable and must be stopped.

This lack of stability mentioned in the wire feeding mechanism, has to be solved in order to obtain good quality clads and the wire end has to be positioned correctly inside the melt pool. In addition, wire feeding rate results to be a critical variable of the process if high quality clads are to be obtained. When the feeding velocity is too high, the wire may not melt and would contact the bottom of the melt-pool, whereas a too small feeding velocity may result in the formation of droplets. For the tests carried out, a 825m/min wire feeding rate resulted the optimum.

4.1. Mechanical properties comparison

In order to compare the mechanical properties of powder and wire LMD test parts, a series of standard tensile tests were performed following the DIN EN ISO 6892-1 standard. In Figure 5, the dimensions of the manufactured parts are shown. The parts were cut by Wire Electro Discharge Machining (WEDM), leaving a 0.2 mm extra material that was removed afterwards by hand polishing in order to eliminate the white layer and any surface microcracks generated during the WEDM process.

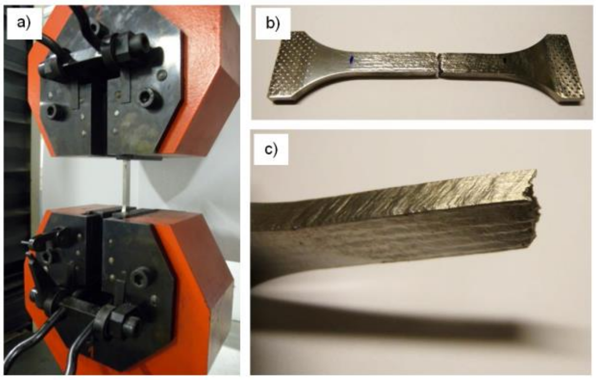
Figure 5: Standard tensile test part.



Two sets of three parts were manufactured order to obtain an average value of the results. The base workpiece was used just as a base material for the LMD process and the tensile test parts were entirely obtained from the deposited material.

Wire tensile test parts are named with the letter “W” whereas powder ones with a “P”. The numbers are used for indexing the specimens after the letter. The order of the numbers is set from the upper one (P1 or W1) to the lower one (P3 or W3). The tensile tests were carried out at a 10mm/min speed and all parts were tested until breakage, while the force vs. clamp displacement diagram was plotted. Figure 6 shows the tensile test of the P2 test probe and the resulting test probe after the breakage. An analysis of the surface of the part shows a stretch mark appearance as a consequence of the directionality of the LMD process.

Figure 6: a) Tensile test of the test part P2. b) Test part P2 after the breakage. c) Detail of the tested part P2.



As it can be seen in Figure 7, parts built by wire reached a slightly higher ultimate tensile stress (UTS) than those built by powder. However, the difference is not higher than 75 MPa, less than 5% (see Table 3) and it can be assured that there is no difference between building the part with powder or wire regarding the ultimate tensile stress.

In order to determine the unitary strain at the breaking point, the deformation of the length between points was measured before and after the tests and the same method was applied with the cross section in order to determine the necking of the parts (see Table 3). The cross section area of the tensile test probes and the length between points were named with the letter “S” and “L” respectively. With the aim of comparing their values before and after the tensile tests, an apostrophe has been added to these seconds. The variation of the cross section and the length between points are named as “ΔS” and “ΔL” respectively.

Figure 7: Average results of the tensile tests for Wire ($\overline{W}$) and Powder ($\overline{P}$) LMD test probes.

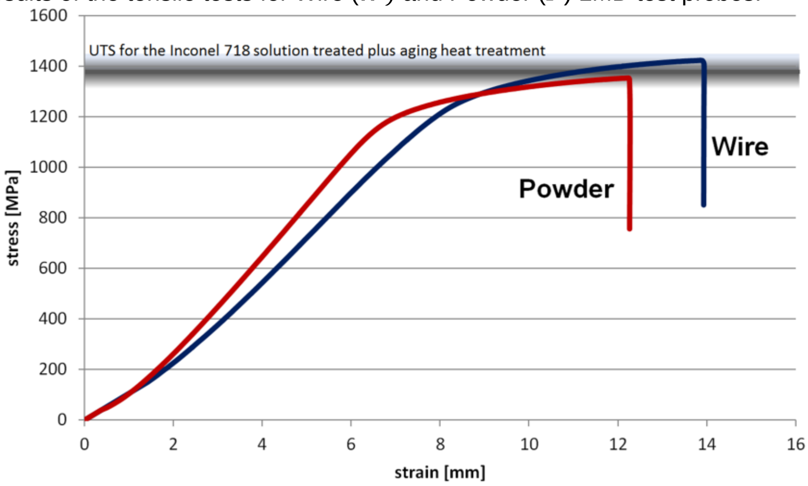
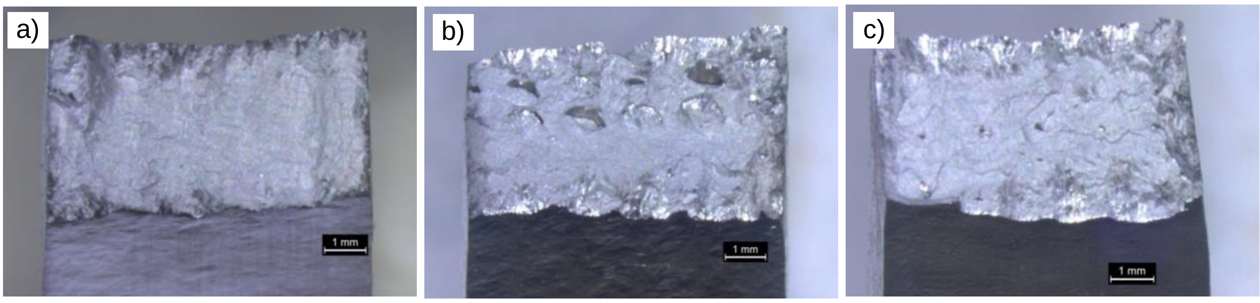


Table 3: Results of the tensile tests.

	W1	W2	W3	$\overline{W}$	P1	P2	P3	$\overline{P}$
S [mm^2]	32.96	32.26	32.11	**32.19**	32.11	31.81	31.80	**31.91**
L [mm]	43.80	42.00	42.10	**42.05**	42.00	43.72	43.60	**43.11**
S' [mm^2]	29.54	29.02	28.03	**28.53**	29.23	28.77	29.87	**29.29**
L' [mm]	47.40	47.50	47.30	**47.40**	46.18	48.37	47.12	**47.22**
ΔS [%]	-10.40	-10.06	-12.71	**-11.48**	-8.97	-9.56	-6.05	**-8.19**
ΔL [%]	8.22*	13.10	12.35	**12.73**	9.95	10.64	8.07	**9.55**
UTS [MPa]	1298.74*	1424.78	1424.36	**1424.57**	1344.55	1354.65	1355.40	**1351.53**

**These lower UTS and elongation values are a consequence of internal defects found inside the deposited material after the tensile tests and therefore the W1 test part was not taken into account in calculating the* $\overline{W}$ *average value.*

Figure 8: Details of the breakage cross sections of powder and wire LMD test parts. a) P3; b) W1; c) W3.



The result analysis shows that the wire LMD parts present a higher deformation and necking at their breakage. Thus, it can be concluded that powder parts show a slightly more brittle nature compared with the wire ones.

Regarding the results dispersion, in all tensile tests almost the same UTS values were obtained. The only exception was the W1 part (the upper one built with wire), which UTS was around 9% lower than W2 and W3 test parts. Nonetheless, it reached an almost 1300 MPa UTS, which is comparable to the value that typically reaches the Inconel 718 parts hardened by a precipitation hardening heat treatment.

The reason for the lower UTS value of the W1 test part was the incorrect bounding between the adjacent clads. This deficiency can be easily detected when the breakage sections are analysed after the tensile test (Figure 8.b), where complete wire sections that have not been melted can be observed. However, this lack of bounding has a minimal effect because of the directionality of the process (clads are deposited in the direction of the forces).

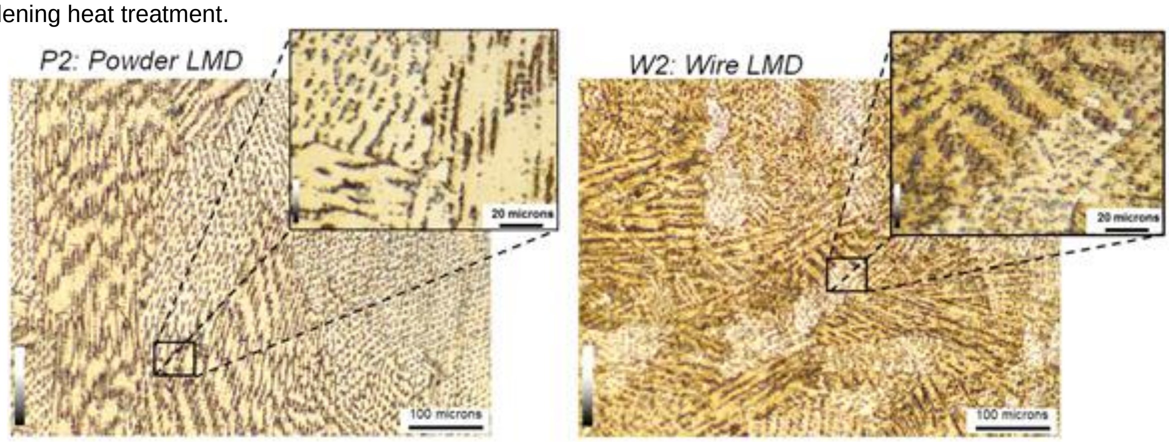
4.2. Microstructure and hardness comparison

Once the mechanical properties were measured, cross sections of both wire and powder LMD parts were polished and etched with a Kalling-II solution in order to see the microstructure and the possible internal defects that may appear during both processes.

The manufactured parts resulted to be free of pores and in all cases a dendritic structure was obtained as a consequence of the fast cooling. In Figure 9 two details of the dendritic structure of powder and wire LMD manufactured parts are shown. The matrix has a γ phase whereas in the interface between two adjacent grains and in the interdentritic zone, the γ'' phase (the primary strengthening phase) has been generated as a consequence of the fast cooling rate of the LMD process.

The microhardness measurement was made with a Vickers indenter and applying a 300 grams load during a 12 second dwell time. The powder part "P2" and the wire part "W2" were analysed. In order to obtain an average value, a total of 10 indentations were performed in each part following a 2x5 rectangular pattern. A 3 mm distance was left between two adjacent indentations seeking to avoid previous indentation effects.

Figure 9: Details of the dendritic microstructure developed by powder and wire LMD parts after the precipitation hardening heat treatment.



As it is shown in Table 4, similar results were obtained for both parts. Therefore, it can be concluded that there is no difference between the powder and wire LMD parts regarding their hardness.

Table 4: Microhardness results.

HRC	**P2**	**W2**
1	50.0	52.8
2	51.2	50.3
3	51.8	52.2
4	50.0	50.3
5	50.0	50.1
6	48.6	50.0
7	51.4	51.0
8	51.1	51.3
9	49.9	51.4
10	50.8	50.7
average	**50.6**	**51.0**

4.3. Process efficiency and time comparison

With the objective of evaluating the efficiency and process time, a complete analysis of the experimental data has been performed. Since mechanical properties, hardness values and microstructure present similar results, the decision between powder or wire LMD process can be driven by these factors.

In the experimental tests carried out in this work, the powder mass efficiency was measured and resulted to be of the 21%. Inside this powder mass efficiency is included not only the non-trapped powder, but also powder losses when the laser is off, such as the powder lost before switching on the laser (in order to ensure a constant powder flow at the nozzle exit) or the amount of powder stored and therefore lost in the conduits when the process is stopped.

However, a deeper discussion about process efficiency has been carried out. In wire LMD the flatness of the surface of the workpiece is critical and any waving may generate an incorrect bonding between the adjacent layers. The lower mechanical properties of the W1 part are justified by this deficient bounding. In order to avoid these defects, the process has to be stopped when this waving is detected, mechanize the surface of the deposited material and generate a flat surface before continuing with the additive process.

Furthermore, due to the sensitivity of the process, every time the wire is adhered to the surface of the workpiece or droplets are generated in the surface, the process has to be stopped and this reduces the process efficiency. This is why, the efficiency of wire LMD is not a 100%, but a slightly lower 92%.

In general terms and using the equipment and process conditions described in the previous paragraphs, the deposition rate for the wire LMD resulted to be twice as for the powder LMD. Therefore, the total time for the deposition of the same geometry is considerably reduced. In Table 5, process efficiency and productivity data are detailed.

Table 5: Powder and wire LMD process efficiency and productivity.

	Powder	**Wire**
Base material weight (kg)	0.85	0.85
Added material (kg)	0.39	0.36
Total material used (kg)	1.85	0.39
Efficiency (%)	21.00	92.00
Time of the process (min)	161.00*	79.05*

** The machine movement feed rate between the consecutive clads was set to 5000 mm/min in order to reduce non-productive times.*

4.4. Process flexibility and cleaning

Nonetheless, there are many factors that may influence the choice between wire and powder LMD that cannot be quantified. Here are included the cleaning of the process, the toxicity of the materials, the flexibility of the process and the sensitivity of the process to the appearance of defects.

Wire LMD process is considered a “clean” process compared with powder LMD, where all the machine finishes covered with the non-trapped powder and has to be cleaned as a consequence of the unhealthy nature of metallic powders. At this point, must be highlighted the toxicity and carcinogenicity of some metallic powders, such as the Nickel powder. This fact must be taken into account before making the right decision.

The storage and maintenance of powder is more complex than that of wire. On the one hand, many materials are prone to their oxidation. Even this is not the case of Inconel-718, this fact is really important when copper or titanium based alloys are stored. On the other hand, powder needs to be preheated in order to remove the moisture and avoid the powder being soggy and sticky, losing its capacity to flow. Therefore, the adequate equipment for the storage and maintenance of powder is required.

Moreover, the price of rough material is much lower in the case of wire LMD. There are two principal reasons for this statement. Firstly, the wire used for the LMD can be obtained by means of wire drawing, which is a much cheaper process than the gas atomization used to obtain the powder particles. Secondly, the availability of a wider range of wire filler materials together with the possibility to use them with conventional systems developed for TIG or Plasma welding makes the wire LMD process cheaper, more flexible and less complex.

On the contrary, the higher flexibility of the powder LMD process, together with a more robust nature, makes easier the programming and control of the deposition process when powder is used as additive material. This is especially critical when complex geometries are to be deposited, because the laser paths for wire LMD could be limited by the deposition directionality. Furthermore, as the wire LMD is a more sensitive process, the machine operator has to be careful about the appearance of errors during the process and stop it in order to solve them.

5. Conclusions

After the realization of the present research work, the following conclusions were reached:

- Both processes, wire and powder LMD, resulted to be capable of building the desired part and there is no significant difference regarding the mechanical properties and hardness of the deposited material.

- Powder LMD resulted to be more flexible and the process is less given to stop due to process errors (drop generation, adhesion of the wire to the base material, etc.). However, wire LMD process resulted to be much faster, what means that when easy geometries and especially big amounts of material are needed to be deposited, this process is in advantage over the powder LMD.

- Parts produced by powder and wire reach similar ultimate tensile stresses, with UTS values around 1350MPa, what is comparable with the value of the base Inconel 718 material. Powder built parts resulted to have a more brittle nature than wire ones, and therefore their elongation before breakage is smaller. This fact must be taken into account when designing functional parts.

- As the efficiency of the wire LMD process is higher than the powder LMD, material waste is reduced. Also the higher deposition rate of the wire reduces the process time. Nevertheless, these process efficiencies and time values depend on the complexity of the manufactured parts.

To sum up, even both technologies are capable of building high quality parts regarding the material integrity and mechanical properties, powder LMD is a more suitable process when complex geometries or all-directional clads are to be generated. On the other hand, wire LMD results to be in advantage when simple geometries combined with higher deposition rates are required for the repair or manufacture of bigger parts.

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