Study Of Nickel-chromium Super Alloys Processed With Plasma Metal Deposition To Enable Additive Manufacturing Of Large Parts

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Abstract

Nickel superalloys are widely used for high performance applications especially at elevated temperatures and in corrosive environments. They are used in industries like space, aviation or (petro-) chemistry. Traditional processing of this material class is difficult. For example, work hardening complicates cold forming or hot cracking is a strong issue for welding.

Within this study Alloy 625 is processed with Plasma Metal Deposition (PMD®), an additive manufacturing process with high deposition rates for large part production. For this alloy blown powder and wire fed manufactured parts are compared to evaluate advantages and disadvantages of both feedstocks. The weldability is studied. To access the performance test coupons are investigated and analysed with respect to the mechanical properties.

Differences in properties between manufacturing components with wire based or powder based feedstock have been identified and compared.

Introduction

In this work the additive manufacturing technology Plasma Metal Deposition (PMD®) developed at RHP-Technology GmbH (Seibersdorf, Austria) was used [1-2]. The PMD® technology is based on a plasma as energy source that melts the material injected in powder or wire shape into the focus of the plasma and deposits it on a substrate as needed [3].

A high temperature plasma is created by introducing argon gas through the torch, where due to a difference of potential gets ionized. This plasma plume creates an electrical contact between the torch and the substrate to ignite the main plasma arc. Around the main arc, an argon shielding gas is injected to protect locally the welding area from oxidizing and external agents during the manufacturing process [4].

The plasma torch is fixed to a gantry system that allows to move it in 3-dimensions over a working table. The size of the gantry system and the working table will determine the maximum size of the produced part, being possible the manufacturing of large-size components [5].

The powder feedstock is injected with the help of a metric wheel feeder and pressurized argon (powder gas) through pipes directly into the plasma focus where a welding pool of molten material is produced. The PMD® process allows the production of large-size components with a high feeding rate (1-10 kg/h) [6-7], being more versatile than manufacturing in a powder bed.

Experimental Approach

Within this study Nickel based superalloys have been studied with respect to their potential for the fabrication by using the PMD® additive manufacturing process. In a first step different candidate materials for the used feedstock (wire or powder) have been analysed and assessed. One of the advantages of the PMD® process is that it is possible to work with wire or powder as feedstock. Especially when using powder, the process has a certain flexibility, e.g. for modification of the composition or for the fabrication of composite materials. It allows to use powders of different size, typically 50-250 µm. If the powder has a moderate flowability through the ducts of the torch, the processing is possible.

- Raw Material Analysis

As shown in the Figure 1a the INCONEL 625 powder had a nominal size range of 45-106 µm with irregular shape. In this case satellites and irregular particles are visible contributing to a larger amount of small sized particles. Satellites attached to the larger particles are present.

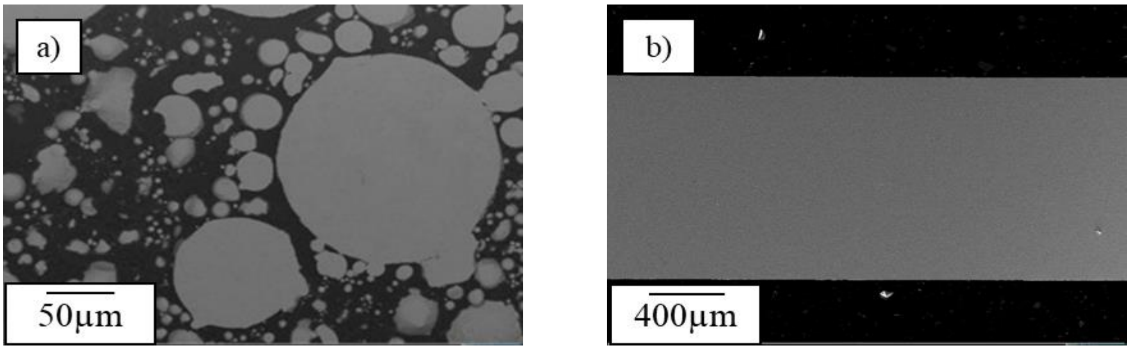

Figure 1: (a) Cross section of INCONEL 625 powder and (b) cross section of INCONEL 625 wire

The second feedstock used was INCONEL 625 in the form of wire. The diameter of the wire was 1.2mm. The cross section of the wire is fully dense and does not show impurities or irregularities (Figure 1b).
For both feedstock materials (wire and powder) in a first step the feeding characteristics were determined in order to check if there is a feeded material deviation from the linear relationship when increasing the feeding rate.

- Test seam preparation

In order to analyze the different feedstocks in a first step test seams using the PMD® process [8] (single seams and oscillated seams) were prepared. Here basically parameters such as Current, Feeding Rate and Travel Speed were varied as shown in the following Table 1 for powder and wire based processes. A Design of Experiment approach was used.

Table 1 Design of Experiment for Inconel 625 powder (left) and Inconel 625 wire (right)

N° TEST	**Current [A]**	**FEEDING [kg/h]**	**TRAVEL SPEED [mm/min]**
1	120	0.9	100
2	140		
3	160		
4	120	2.0	200
5	140		
6	160		
7	180		
8	200		
9	120	3.1	300
10	140		
11	160		
12	180		
13	200		
14	220		
15	220	3.6	400
16	250		
O1	160	0.9	150
O2	200	2.0	270
O3	200	1.2	
O4	180		

N° TEST	**Current [A]**	**FEEDING [kg/h]**	**TRAVEL SPEED [mm/min]**
1	120	1.6	200
2	140		
3	180		
4	220		
5	120	1.0	100
6	140		
7	160		
8	140	2.3	300
9	180		
10	220		400
11	240	3.6	
12	210	2.2	200
O1	210	1.7	350
O2	210	1.5	300
O3	150	1.4	200

The resulting test seams are shown in Figure 2. All settings result in closed, straight weld seams without a macroscopic defect. High energy input leads to a wider melt pool and shows a better wetting (see test No 3, 8, 13, 14, 16, O3 and O4). Thicker walls were produced with oscillation technique O3 and O4 which are suitable for the first layers of the wall as high energy parameters are used, whereas O1 is more suitable for the upper part of the wall as low energy parameters are here used. For the powder-based materials it is also visible that there is a certain overspray observed. Typically, this was in the range of 5-15 % which has to be considered as material which cannot be re-used due to possible contamination.

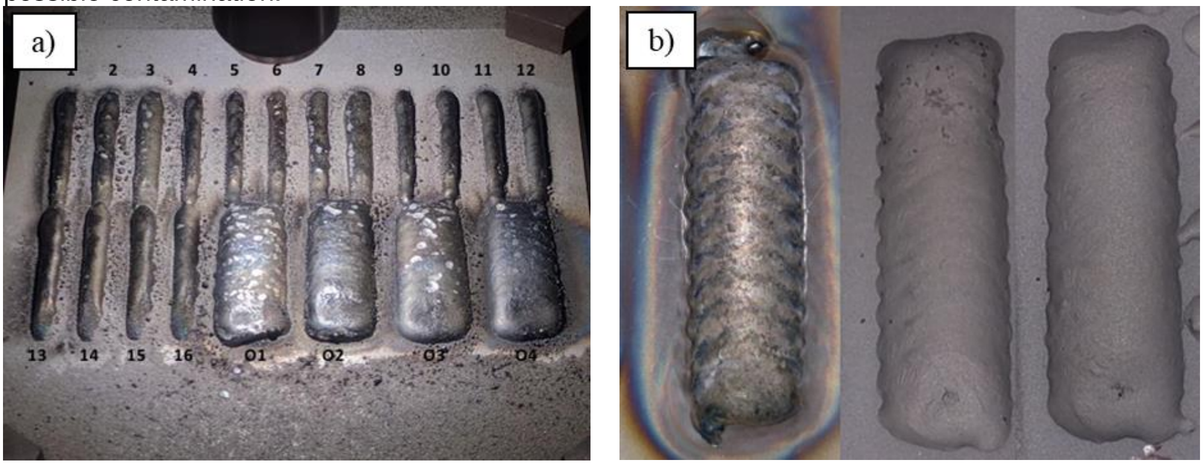

Figure 2 (a) Test seams prepared from INCONEL625 used powder based process and (b) using wire based process

Based on the evaluation and microstructural analysis of the best conditions from the test seams a wall was prepared using the following parameters for each material/process. The following Table 2 shows the information the main processing parameters used for the deposition of the test wall.

Table 2: Overview on processing parameters used for the manufacturing of L-type test structures (see Figure 3)

	INCONEL625	
	Powder	Wire
Atmosphere	Ar	Ar
Feeding rate [kg/h]	0,9	1,9
Current [A]	140-200	140-200
Deposition efficiency [%]	87	100

For each material an “L-type” structure was prepared allowing to subsequently extract tensile test samples from different orientations (horizontal and vertical).
Since the walls have been prepared by using an oscillation mode it was possible to extract several tensile test samples. This allowed also to perform additional subsequent heat treatments on the tensile test samples.
Two heat treatment conditions have been assessed:

- 3°C/min, 900°C, 2h, 3°C/min, RT, in argon atmosphere.
- 3°C/min, 1000°C, 2h, 3°C/min, RT, in argon atmosphere.

From the extracted samples tensile testing was done according to DIN EN ISO 6892-1.

Results

After preparation of the test walls, samples for the cross section analysis were extracted. In Figure 4 micrographs of both materials are shown.
The microstructure shows a dendritic microstructure consisting of two phases, a dark grey colour Ni-matrix consisting on γ-Ni as suggested in [10] and white lines/Laves phases riched in Nb and Mo [11] aligned in x-direction. The Laves phases anisotropically precipitated on the preferred x-direction (Figure 4) as well as existing micro-porosity may affect the mechanical properties. Moreover, the plasma metal deposited process results in larger sized grains compared to as-casted samples [12].

The mechanical results achieved from INCONEL 625 wire and power are compared in the following Figure 5 and Figure 6. The following diagram shows the results of yield strength, tensile strength and elongation achieved on the walls from samples extracted on horizontal and vertical position (Figure 3) as well as in the as built conditions and after heat treatments at 900°C and 1000°C.

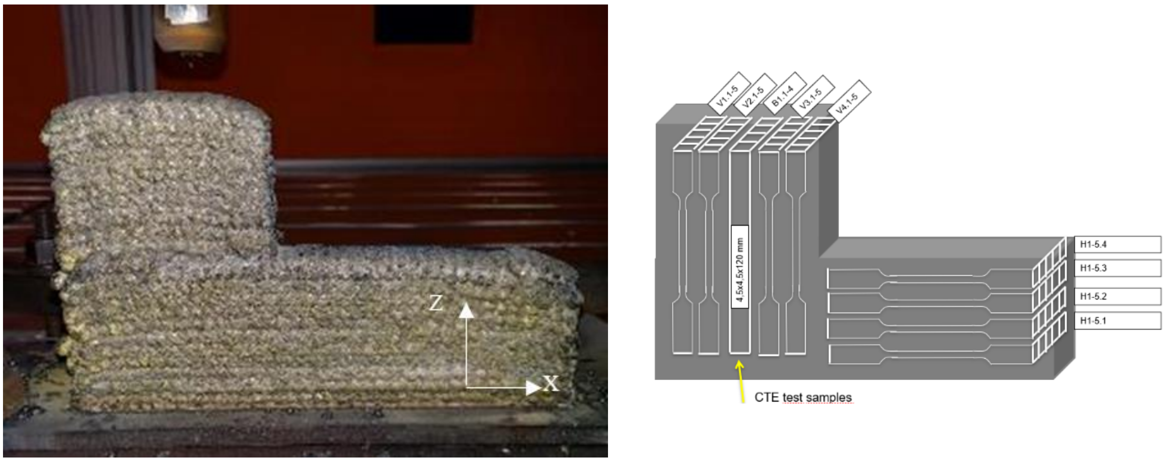

Figure 3: INCONEL 625 test wall and schematic overview on the extraction of the tensile test samples.

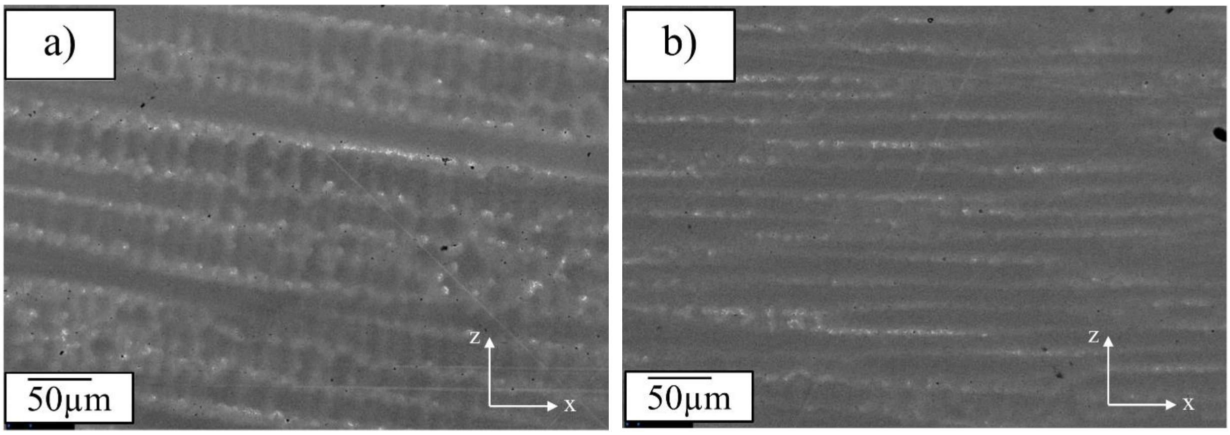

Figure 4: INCONEL 625 microstructure made by PMD® using powder (a) and wire (b) as feedstock material.

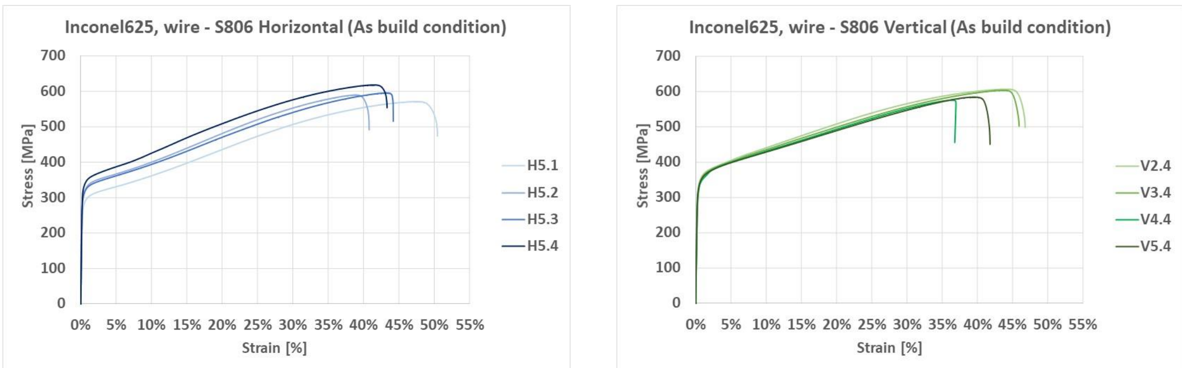

Figure 5: Tensile curves from wire-base feedstock INCONEL 625 manufactured by PMD®.

When comparing both technologies it can be summarized:

Yield Strength:

- The powder based process results in more anisotropy between the horizontal and vertical values. Typically, vertical samples are slightly higher in the yield strength. This trend is still present after the heat treatment. In comparison to the reference similar values of around 330 MPa have been achieved.
- Wire based process shows less anisotropy. Values comparable to the reference values have been achieved.

Ultimate Tensile Strength (UTS):

- In the powder based processes the anisotropy of tensile strength properties is even more pronounced. Vertical samples result in a higher strength. Both heat treatment do not improve the properties.

- In the wire based process more uniform properties are observed. The values after the two different heat treatments applied are in a similar range. The achieved values are aprox. 10-15 % lower compared to the reference.

Elongation:

- The powder based process shows a very high degree of anisotropy. While the horizontal value is around 20% and decreases with increasing heat treatment temperature, the values for the vertical direction are more than two times higher (approx. 45 %).
- Wire based process again shows more isotropic behavior and values of around 45% which are higher compared to the reference (ca. 35%).

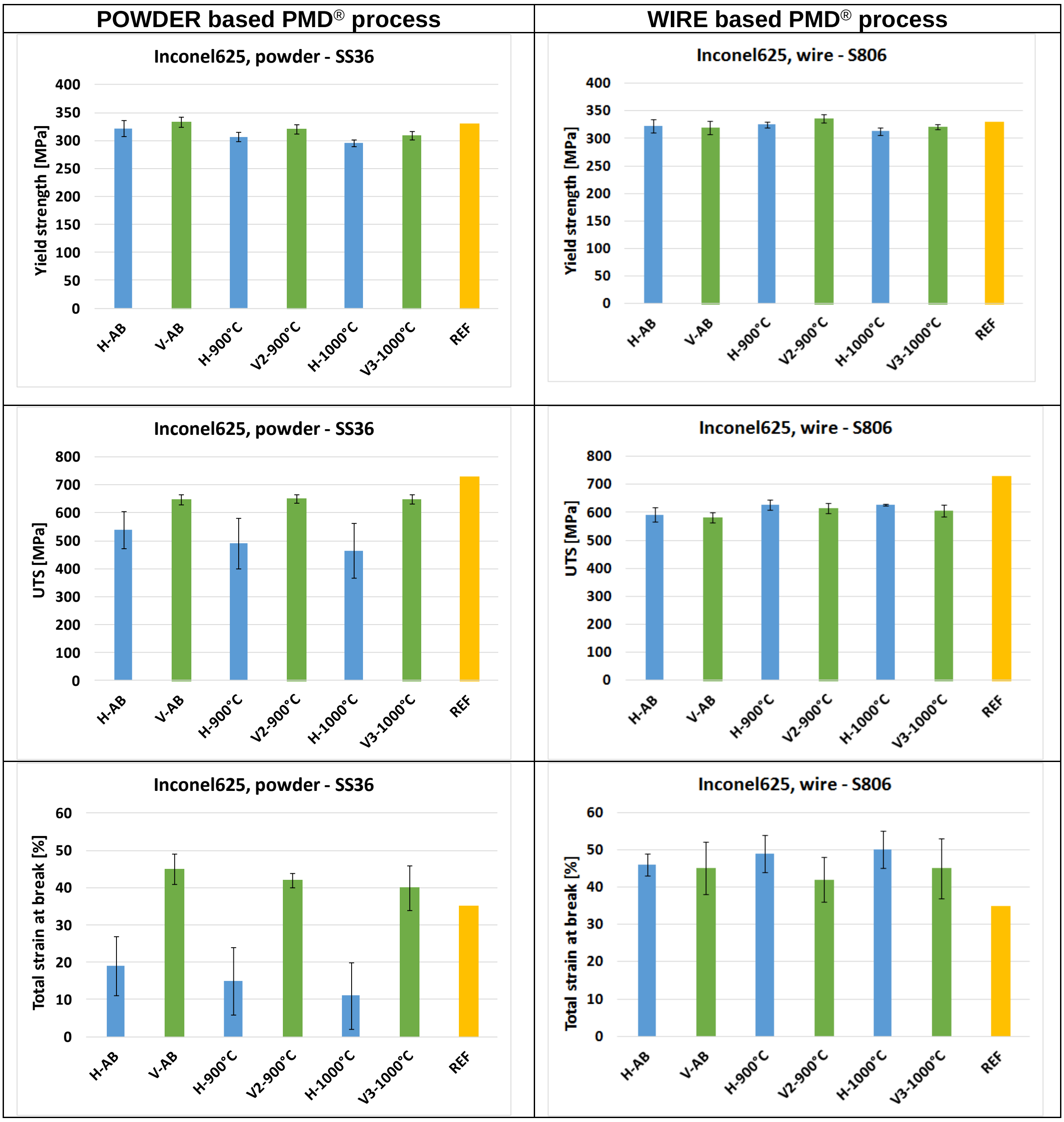

Figure 6: Yield strength, ultimate tensile strength and elongation at break of tensile samples prepared by PMD® process from Inconel 625 powder (left) and compared with (right). For comparison reference values from VDM Metals GmbH [9] are presented. *H-AB: horizontal as built; V-AB: vertical as built; H-900°C: horizontal after heat treatment at 900°C; V-900°C: vertical after heat treatment at 900°C; H-1000°C: horizontal after heat treatment at 1000°C; V-1000°C: vertical after heat treatment at 1000°C;*

Conclusion

Inconel 625 is a very promising material for additive layer manufacturing using PMD®. The use of a wire-based process is more practical, and it has better properties than the powder-based process. The flowability of the powder injected through the PMD® torch, although not fully spherical, is good and the deposition efficiency of Inconel powder is reasonable (in a range of around 85-90%). Deposition rates in the range of 1-2 kg/hour were achieved with the potential to increase it to 3-5 kg/hour. This makes the technology particularly of relevance for large structures.

Especially the powder based process results in large grains, more remarkable in Z-direction. This is also directly reflecting the anisotropy in the properties. Typically, the perpendicular direction (Z-direction) is resulting in higher mechanical property values. Both heat treatments applied did not significantly change/improve the properties. Due to the coarse grains no change in the microstructure is achieved.

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