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Analysis of the Anisotropy of Properties in Titanium Alloys made by Plasma Metal Deposition

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Abstract

Plasma Metal Deposition (PMD) is a Direct Energy Deposition (DED) method which allows to manufacture large metallic structures. This method allows to use wire or powder as a feedstock. Using powder allows to reach higher geometrical accuracy. When building large components, it is important to get an information on the mechanical performance. Therefore, properties were measured at different building heights. The anisotropy of the mechanical properties in horizontal and vertical building direction was analysed by taking samples in these orientations. Typical components contain different features such as T-nodes or crossing points. These features have been analysed in detail, especially with respect to the microstructure and a possible influence of defects on properties.
Besides the tensile strength, yield strength and elongation also the hardness and the microstructure were investigated. The influence of heat treatments on properties and microstructure was analysed.

Introduction

Additive Layer Manufacturing (ALM) is a manufacturing method to produce parts close to the final shape or ready to use. While in powder bed processes many parts need only surface treatments and machining of some functional areas, the situation in blown powder methods is different. These processes, also called Direct Energy Deposition (DED) methods, are combining different heat sources such as laser [1], electron beam [2] or standard welding techniques as. MIG, TIG or plasma arc [3-6]) with an appropriate “feedstock material”. The feedstock can be either wire, powder or a combination of both.

These types of “shape welding” techniques offer the advantage to manage deposition rates such as 1-10 kg/hour which is significantly higher compared to powder bed processes. On the other hand, the precision is in the range of 0,1 to 1 mm depending on the used technology. Most of the built parts require a subsequent machining step. One of the main application areas of this type of processes is for components which have a high “buy to fly” ratio. Examples from aeronautic industry show that in some cases 5 - 10 times the weight of the final part is required as raw material for complete machining. A fast building rate – even if it is not that precise – allows to save a lot of raw materials. Especially in the case of titanium the value of saved raw material can be quite high.
Therefore, this activity is focused on studying the properties and their anisotropy of Titanium alloys prepared using a Plasma Metal Deposition process.

Process

Plasma Metal Deposition (PMD) is a technique which uses a torch where the plasma is produced for melting of materials. To prevent that the plasma melts, the torch is cooled with water by internal cooling channels which are connected to a chiller.
The gas used to produce the plasma is Argon and it is introduced between the electrode and the copper cylinder (pilot gas). At the same time, an external copper cylinder can be used to introduce another gas that acts as a shield (shielding gas) and prevents the weld seam from oxidizing during the process or from other external gases entering the weld pool.
The shielding gas is only a local protection. To produce oxygen sensitive materials such as Titanium alloys, the whole process is done in a chamber which is operated under Argon atmosphere.
For the creation of the plasma, a potential of 20 V is applied between the electrode and the copper cylinder. With this potential and with the pilot gas, a plasma is produced that acts as a pilot. The pilot makes it possible that the plasma arc starts between the electrode and the substrate that is connected to the ground. The material is injected as powder to the plasma flame through feeding holes. For making the powder flow better through the channels, it is injected with a pressurized gas (powder

gas), which is usually Argon. Additionally, the material can be introduced in wire shape externally to the torch. It is necessary to ensure a correct alignment between the wire and the focus of the plasma flame in order to have a good melting efficiency. The torch is fixed to a mechanical axis system (x-y-z portal), which allows the torch to move through a working table. The working table is built with aluminium profiles cooled to ensure the heat transfer through the system.

Materials

For the selection of the starting material Ti6Al4V powder and wire have been used with specification according to the ASTM standard. The powder of Ti6Al4V has a particle size between 106 µm to 180 µm. The following Figure 1 (a) shows a SEM image of the TI6Al4V powder showing a good sphericity. Although there are some small satellites attached to the powder, the powder shows a good flowability.
The wire which was used had a diameter of 1.2 mm and the following Figure 1 (b) shows the surface of the wire. The wire shows in the cross section no impurity and porosity using SEM/EDX analysis. The surface has a bright appearance.

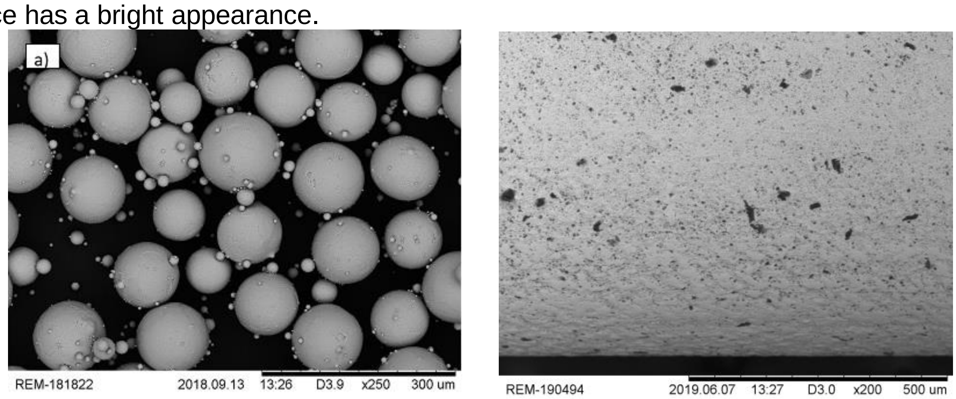

Fig. 1. Ti6Al4V raw materials used for the PMD process, a) SEM of Ti6Al4V powder (250x), b) SEM of surface of a Ti6Al4V wire (200x)

While the use of the wire is straight forward and the feeding rate is directly proportional to the driving wheel, the situation with the powder is different. In this case the feeding rate is evaluated in a first step (Fig. 2). One of the observations when using powder is the sticking of partial melted powders in the injector nozzle. This is subsequently creating a clogging resulting in an interruption of the powder feeding. To avoid this issue a proper design of the injection nozzle is required and additionally efficiency of the cooling of the torch is required.

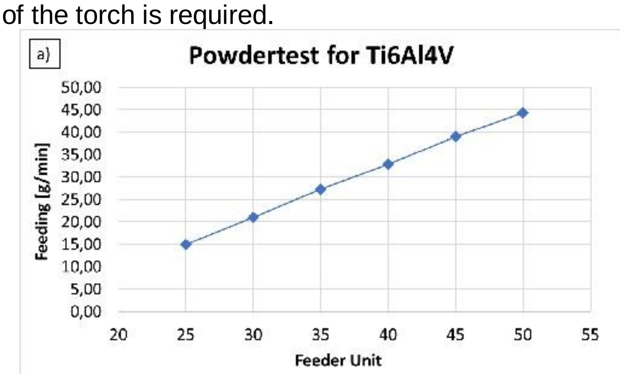

Fig. 2. a) Powder test for Ti6Al4V powder

Manufacturing

In order to identify the influence of the layer by layer structure on the mechanical properties, test structures have been prepared by using powder and wire feeding technique. The PMD process was used to prepare test structures using the following conditions shown in the Table 1.
By using these processing conditions, a defined structure was prepared. This test structure is shown in Figure 3. Samples were extracted in different directions (horizontal, vertical, diagonal). One half of the test structure was cut and subjected to a heat treatment. The heat treatment was carried out in the following conditions: 600°C in Argon atmosphere for 2 hours.

Table 1. Processing parameters of TiAl6V4 structures.

Process	Plasma Arc Current [A]	Voltage [V]	Pilot Gas Flow [l/min]	Shielding Gas Flow [l/min]	Powder Gas Flow [l/min]	Feeding rate [kg/h]	Welding Speed [mm/min]
Ti64 Wire Feed	150	20	1.5	10	-	1.5	600
Ti64 Blown Powder	140	20	1.5	10	1.5	1.2	600

Subsequently to the manufacturing/heat treatment of the test structure tensile test samples were extracted from different positions. The tensile testing was carried out using an Instron 5505 equipment. From the stress-strain curve the yield strength and ultimate tensile strength were derived as well as the Young´s modulus and the elongation at fracture.

In total 4 different conditions are summarized and compared:

a) Test structure made by blown powder method (as built)
b) Test structure made by blown powder method (heat treated)
c) Test structure made by wire feeding method (as built)
d) Test structure made by wire feeding method (heat treated)

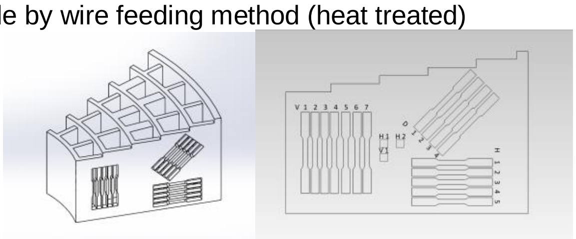

Fig. 3. Test structure (a) and extracted test wall with the position of the tensile test specimen (b) in horizontal, vertical and diagonal position

Results

a) Comparison of wire feed and blown powder in “as built” conditions.

<u>Tensile test results</u>

The first comparison is showing the results of the tensile tests obtained from the structure processed by the blown powder method in the as built conditions (Fig. 4). As can be seen in Figure 4 in most of the samples a value is observed for Young´s Modulus of around 110 GPa.

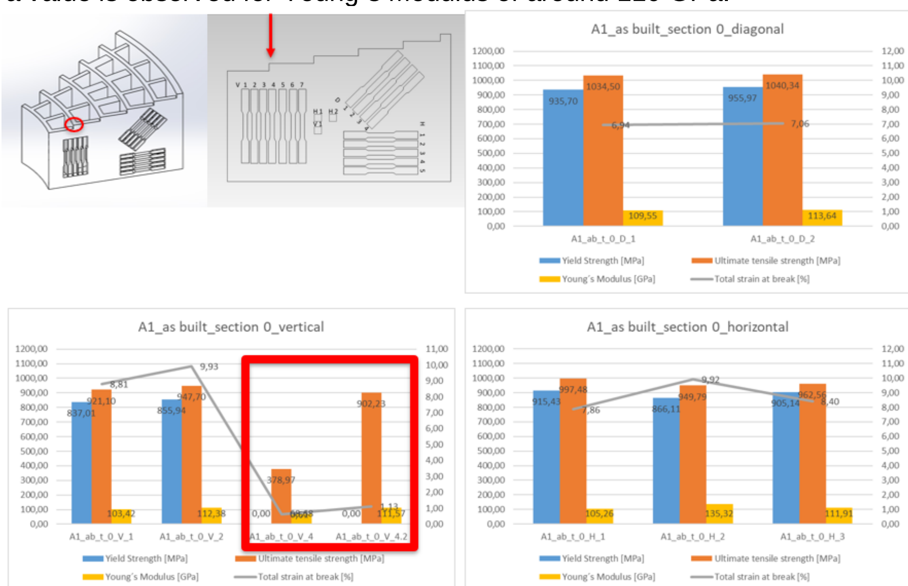

Fig. 4. Summary of tensile test results in horizontal, vertical and diagonal direction from samples prepared by the blown powder method.

Horizontal and Vertical samples have similar properties of elongation (ca. 8-10%), a yield strength of 850 MPa and a tensile strength of 950 MPa. On the other hand, diagonal samples show a slightly higher tensile strength properties reaching 1050 MPa but a reduction on the elongation to 7% is observed. Samples extracted directly from the crossing points in vertical orientation show a very poor behaviour. Their mechanical properties are neither good in elongation nor in the tensile strength (Fig. 4). This behaviour can be explained by local building defects, especially voids.
Taking a look on the samples processed by the wire feeding method we see a slight difference. In general, a lower tensile strength is observed and the difference between the yield strength and tensile strength is not that pronounced. On the other hand, these samples show higher elongation values compared to the blown powder method.
Especially in the vertical position more than 10 % have been measured. For the diagonal samples lower elongations (approx. 4-6 %) are observed.

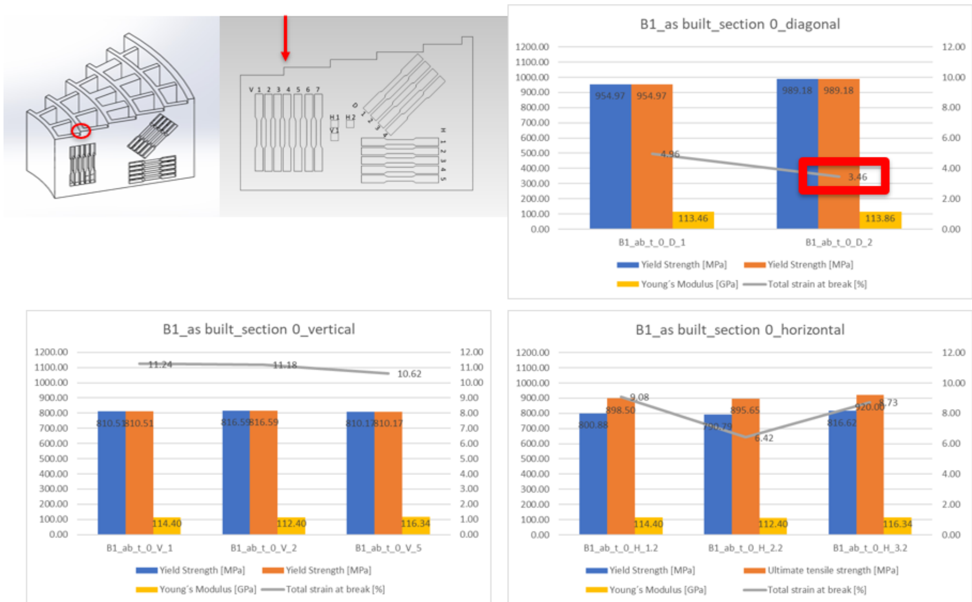

Fig. 5. Summary of tensile test results in horizontal, vertical and diagonal direction from samples prepared by the wire feeding method.

<u>Microstructural characterisation</u>

The microstructural analysis shows in the "as built" conditions no severe defects or porosity. The porosity level of the measured samples is less than 0.1 %. Microporosity is calculated from densification analysis of the tensile test samples using the Archimedes method. In the cross section the Fig. 6 (left) shows at low magnifications that the microstructure is consisting of large columnar grains in the vertical direction growing through several deposited layers. With a higher magnification the microstructure shows the Widmanstätten microstructure of α-grains in β-matrix for both, wire and powder samples.

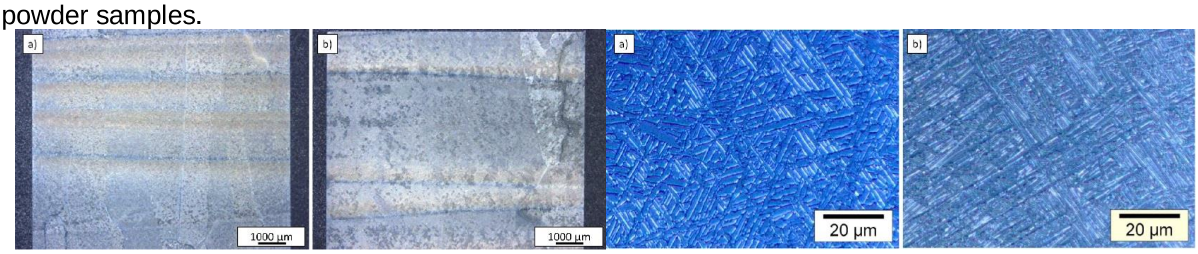

Fig. 6. Microstructure of samples made by blown powder method (a) versus wire feeding method (b) with low magnification (left) and with higher magnification (right)

b) Comparison of wire feed and blown powder in "heat treated" conditions.

<u>Tensile test results</u>

After the heat treatment it can be observed that the Young´s Modulus of the samples has not been affected. For blown powder samples (Fig. 7), vertical and horizontal samples increased their elongation to 10% while keeping the tensile strength at constant level. For the diagonal samples elongation drops to 5% but the yield strength increase slightly to 1000 MPa. Similar to the “as built” conditions, vertical samples placed in crossing nodes have poor elongations.

Fig. 7. Summary of tensile test results in horizontal, vertical and diagonal direction from samples prepared by the blown powder method in the heat-treated condition.

In case of samples taken from wire feed process (Fig. 8), horizontal samples increased their tensile properties slightly with an elongation of 10%. A yield strength of 850 MPa and tensile strength of 920 MPa was measured. For diagonal samples elongation drops to 2-3% keeping the yield and tensile strength constant. Vertical samples in heat treated conditions show similar behaviour compared to the “as built” materials.

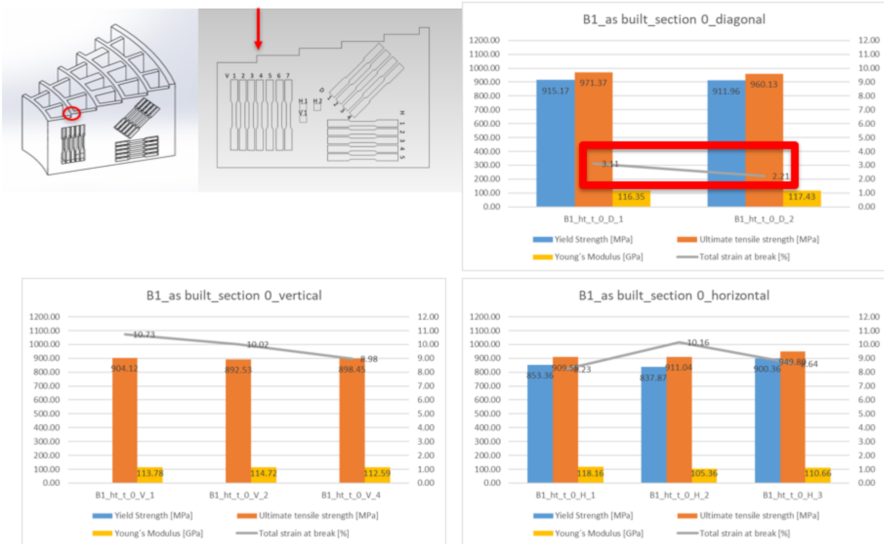

Fig. 8. Summary of tensile test results in horizontal, vertical and diagonal direction from samples prepared by the wire feeding method in the heat-treated condition.

Microstructural characterisation

The microstructural analysis shows in the as heated conditions a homogenous microstructure. The porosity level of the measured samples is less than 0.1 % using Archimedes method. In the cross section the following Figure 9 shows that the heat treatment has not significant impact on the microstructure.

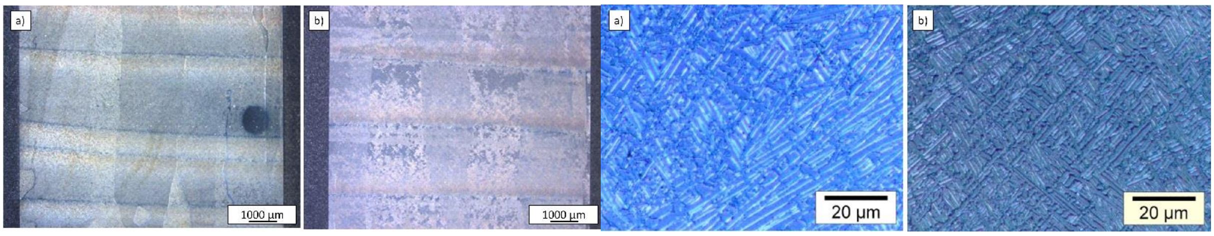

Fig. 9. Microstructure of heat-treated samples made by the blown powder method (a) versus wire feeding method (b) with low magnification (left) and with higher magnification (right)

Conclusions

- Manufacturing: Samples have been manufactured with a building rate more than one kilo per hour with a material deposition efficiency of 90% when using the blown powder and with a deposition efficiency of >98% when using wire feeding.

- Densification: Samples have a densification of > 99%, in some areas micropores were observed, building defects are mainly voids located in T- and X-nodes. These can be solved by appropriate change of the building parameters
- Microstructure: Columnar growth of primary β-grains along the z-axis and perpendicular to the deposition direction. The β-grains are several tens of mm long. A Widmanstätten microstructure of α-grains in β-matrix is observed for all samples. The microstructure has not been affected by the heat treatment.
- Tensile properties: A difference in the properties between wire feeding and blown powder can be explained by a higher oxygen concentration in the parts manufacture by blown powder process. Higher strength, but lower elongation is well known for this condition. Consequently, there is a tendency for higher elongation in the wire based samples. In general, higher tensile strength values are reported in horizontal direction compared to the vertical directions. Samples located in T- and X-nodes have poor tensile properties due to building defects and require an optimisation.

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