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Reviewed Paper

A small volume, local shielding gas chamber with low gas consumption for Laser Wire Additive Manufacturing of bigger titanium parts

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Abstract

This paper shows how additive manufacturing of large size titanium parts can be achieved by means of a mobile shielding gas chamber, without the consumption of excessive amounts of shielding gas. While welding, the oversized cover of the chamber can be slid to the sides without opening it. The laser head is only partly inserted into the chamber through the cover. This enables a small sized chamber and allows a quick filling with argon. Since the chamber has a low leakage, only small amounts of argon (5 l/min) are needed to maintain a sufficient welding atmosphere with less than 300 ppm oxygen. For large sized parts, the chamber can be repositioned on the substrate. It has flexible parts which can be fit to the already welded structures that otherwise would prevent the chamber from being put flat on the substrate. The limited build space inside the chamber requires a new welding strategy, which is suggested.

Introduction

Additive Manufacturing (AM) has a promising economical potential for aerospace applications, especially for bigger titanium parts where sometimes over 90 percent of the material is taken off by milling. In these cases, many of the expensive alloys like Ti-6Al-4V can be saved. Since titanium has a high affinity to oxygen at elevated temperatures, a shielding gas atmosphere has to be applied during welding until it has cooled below 430°C (800°F) [1,2] to protect it from oxidation. Oxygen is an α-phase stabilizer like aluminum in contrary to the vanadium, which is a β-phase stabilizer. If present at elevated temperatures during welding, it leads to the so-called α-casing, an oxidation that can be seen by the discoloration of the surface. The more oxygen the titanium picks up, the more α-phase will be present, leading to an increase of brittleness and a decrease of ductility.

In general, there are three different ways to protect titanium from oxidation. The use of a vacuum chamber is one possibility. This technique is mostly used when welding with an electron beam, since the process requires a vacuum. Establishing a vacuum is a rather slow process, especially in a big chamber. For this reason, a protection gas chamber is more common when welding metals with high affinity to oxygen or other gases with impact on the microstructure. A literature research reveals a broad range regarding the level of oxygen content in the argon atmosphere and seems to be dependent on the type of AM process. Ding et al. [3] found that the hardness of WAAM (wire arc additive manufacturing) welded Ti-6Al-4V components were not affected by an oxygen content of 4000 ppm in the argon atmosphere. Therefore, they selected 2000 ppm as a conservative environmental contamination level. Caballero et al. [4] also investigated the effect of oxygen in TI-6Al-4V with WAAM. They found that tensile properties are not compromised by an increase of oxygen content in the shielding gas of up to 4000 ppm. High temperatures and exposure times seem to have a greater effect on oxidation than the oxygen content in the shielding environment. They also found that different oxygen contents in the wire do not have a significant effect on the thickness of the alpha case. Halisch et al. [5] used a WAAM process in a protection gas chamber to evaluate the influence of oxygen content in the shielding on the mechanical properties of TI-Al6-V6 parts. They concluded that with oxygen levels of up to 6000 ppm the requirements on tensile properties for aerospace parts could be reached, even though yield and tensile strength increases with the oxygen level while the elongation decreases. Gushchina et al. [6] investigated the influence of the oxygen levels in the protection gas atmosphere during additive manufacturing of Ti-6Al-4V using a laser powder DED process. Growth of oxygen concentration until 0.25% O_2 led to change of mechanical characteristics. The best mechanical properties by strength to ductility ratio were produced with 0.25% oxygen concentration in chamber. The author did not specify whether weight or atomic percentage is meant. Since weight percentage would result in 1000 ppm oxygen content this is presumed by the author of this study. Chekir [7] printed Ti-6Al-4V parts using a laser wire process in a process chamber with below 60 ppm oxygen in the argon environment to prevent excessive oxidation. Dai et al. [8] kept the oxygen content below 200 ppm to impede oxidation for wire laser AM with an oscillating laser beam. Gibson et al. [9] used a laser hot-wire process to print Ti-6Al-4V parts. A chamber with a flexible bag on top was used to maintain an atmosphere with oxygen levels under 300 ppm during metal deposition. The printed part nevertheless exhibited yellow and blue oxide in some regions. Velasco-Castro et al. [10] report an increase in hardness and a decrease in ductility of titanium parts manufactured by LPBF (laser powder bed fusion) in an inert gas atmosphere with 1000 ppm oxygen content. Emminghaus [11] showed that the most influential factor concerning the mean hardness in Ti-6Al-4V parts manufactured with LPBF is the residual oxygen content. Pauzon et al. [12] found that an oxygen control to 100 ppm is required to impede these effects in LPBF. Tapoglou et al. [13] realized a protection gas atmosphere for additive manufacturing of titanium using a tub on the bottom and a plastic bag on the top. Argon flow rates of 50 l/min were applied to the chamber reaching oxygen levels of 100 ppm. The AM process used Ti-6Al-4V powder with a flow rate of up to 12 g/min (0.72 kg/h) at 2000 W laser power. This results in a high use of argon and only 0.24 g titanium per liter argon can be build. Yu et a. [14] used a laser powder DED process to build Ti6Al4V parts. The parts were built without the use of an inert gas chamber but with local protection using an argon gas flow provided by the powder nozzle. The maximum powder flow was 1.98 g/min or 119 g/h at 570 W laser power with a protection-gas flow-rate of 10.5 l/min. This means a relatively low heat and material input compared to laser wire processes. The process uses high amounts of argon. Only 0.189 g per liter argon can be build. As mentioned before, AM of titanium has a promising economical potential. This can be increased by reducing the amount of argon used for the building process.

Experimental and Results

To reduce the argon consumption needed for a sound protection-gas-atmosphere when manufacturing bigger parts, a new chamber concept (Figure 1) has been tested. The inner volume of the chamber has a volume of 5.5 l and encloses only a small part of the welding head. In order to manufacture bigger parts, the chamber can be moved successively along areas to weld. The cover of the chamber is slid to the sides by the movement of the laser head. Since it is bigger than the chamber itself, the chamber will not open during this process. A cylinder, which is attached to the laser head, allows vertical motions. When placing the chamber in a new location, build-up parts may block the chamber from being put flat on the surface, hindering the establishment of an intact protection-gas-atmosphere. Therefore seals are installed, consisting of thin metal rods, which can individually be moved vertical and allow to adapt to obstacles.

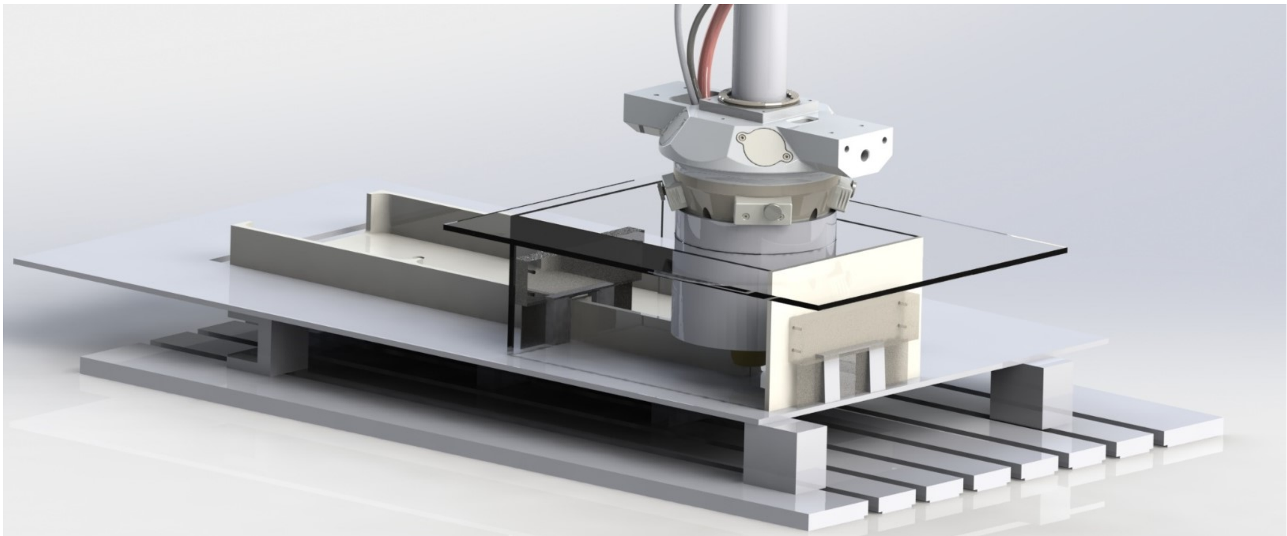

Figure 1: Rendering of the protection-gas chamber on a planned work piece with adaptive seals and partly immersed laser-head.

Even though oxygen contents of about 4000 ppm in the protection-gas-atmosphere without significant impact on the mechanical properties have been reported, a threshold of 300 ppm has been chosen by experience in titanium welding. Applying this threshold has previously led to additively manufactured parts without discoloration from oxidation. To determine a minimal argon flow rate that provides the desired atmosphere in a feasible time, different flow rates have been tested. The oxygen content was measured by a zirconium based sensor with a relative error better than 5%. Through a hole in the base plate directly under the nozzle, the atmosphere was pumped to the sensor. The nozzle had a distance to the base plate of 6 mm, what is a typical process height. Since the atmosphere in the chamber might have deviations in the atmosphere composition at the beginning of each test, the data from 500 ppm to 300 ppm oxygen content was analyzed. The time from first reaching 500 ppm to the point where 300 ppm was not exceeded anymore was measured. Figure 2 displays the graphs of these measurements with three different argon flow rates of 5, 6 and 7 liter per minute.

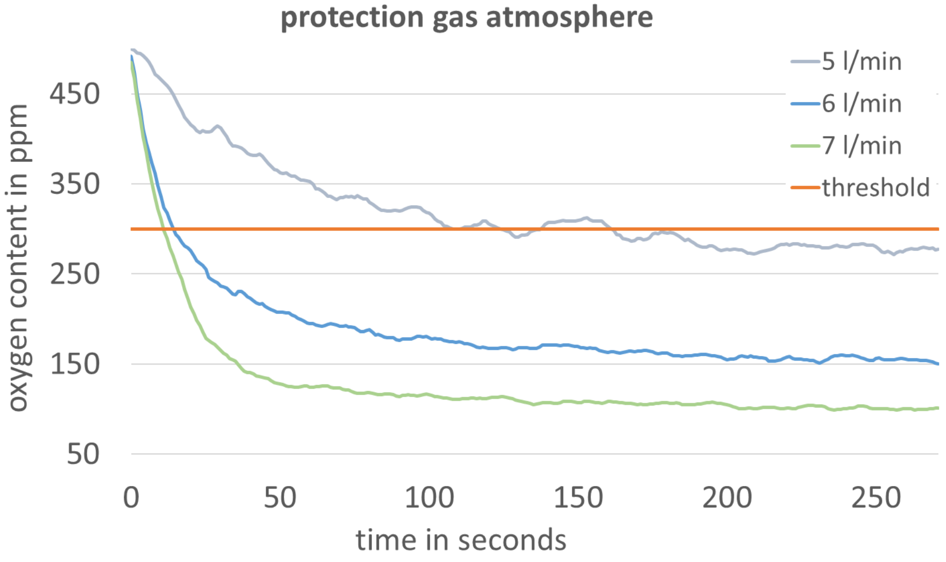

Figure 2: Oxygen decay in protection gas atmosphere for different argon flow rates

The first measurement, carried out at 5 l/min took 162 s to safely reach the desired atmosphere of 300 ppm oxygen content. With 6 l/min, the time was shortened to 15 s and with 7 l/min to 11 s. Since low argon flow rates are desired, 6 l/min argon flow rate was chosen for further testing.

Controlling the oxygen content of the atmosphere is most important at elevated temperatures. With increasing distance to the processing area, the titanium had time to cool down and therefore the affinity to oxygen is reduced. This means more oxygen can be tolerated. A test has been conducted to measure the oxygen content in respect to the nozzle center, respectively the processing area. A value has been taken every other mm from a distance of 2 mm until 40 mm. Each measurement took roughly 3 min. The last 100 seconds of the measurement were used, taking a value every second. Therefore, 100 values were taken for each distance. The results are displayed in Figure 3. Within a distance of 36 mm to the center of the nozzle, the average oxygen content is below the threshold of 300 ppm. Away from the nozzle center, the standard deviation rises as the values increase. Within the 100 values taken for each measurement the maximum value was determined and never reached 300 ppm within a distance of 30 mm.

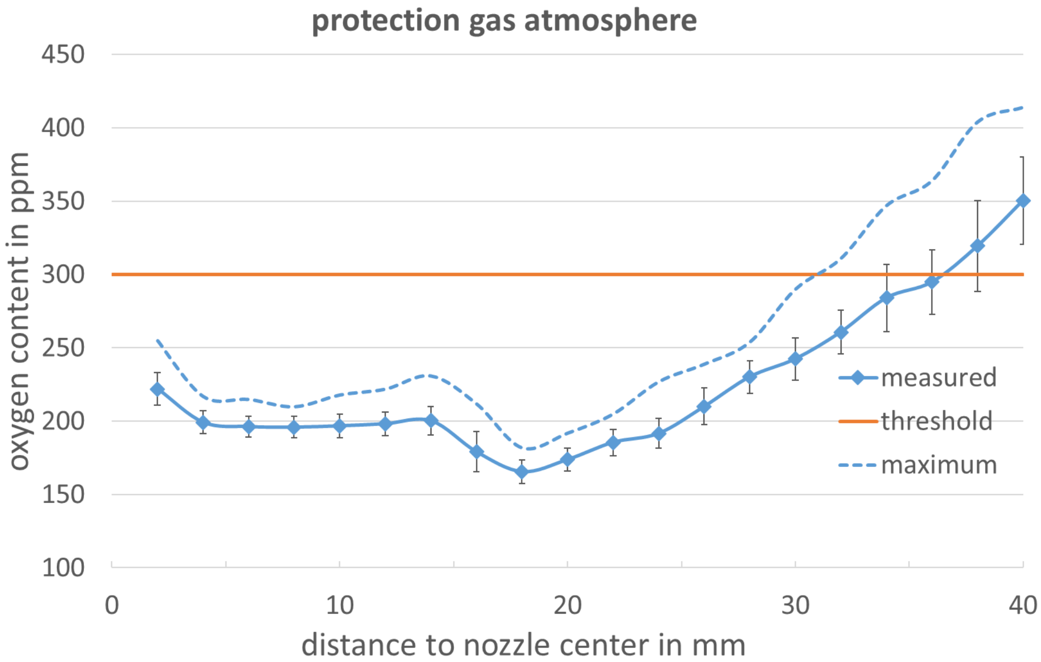

Figure 3: Oxygen content in respect to the distance to the center of the nozzle

To test the setup a weld with Ti-6Al-4V has been performed. A simple bi-directional meander with four lines has been welded on a substrate. The travel speed was 1000 mm/min, wire-feed was 2 m/min and the laser power 1100 W. No discoloration from oxidation is visible on the specimen. Therefore, it is clear that the protection-atmosphere was intact. Figure 5 displays a microsection from the welded Ti-6Al-4V sample shown in Figure 4. The microsection has been grinded and polished and etched with “Weck”.

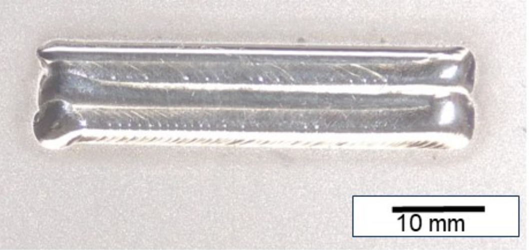

Figure 4: Ti-6Al-4V weld

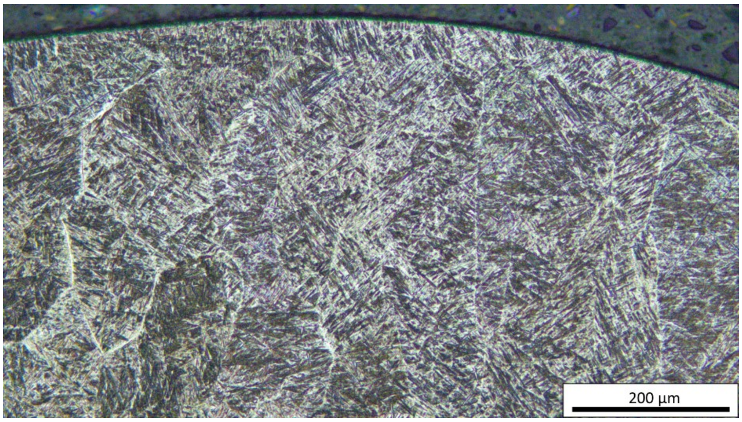

Figure 5: Microsection of the welded Ti-6Al-4V sample

A martensitic microstructure from rapid cooling can be seen in the microsection. Alpha-casing due to oxygen in the protection gas atmosphere would be displayed as a white region on the border of the weld. It absence underlines the feasibility of the low argon gas flow welding technique.

Conclusion and Outlook

The surface quality of the welded specimen which does not show any discoloration from oxidation proofs the feasibility of the protection concept. With 6 l/min argon gas flow, it is possible to weld structures that comply with the needs of Titanium parts. The concept allows to build 1.16 g titanium per liter argon what is more than five times the mass per liter argon reported by [13][14]. A drawback is the limited welding length inside the chamber. This constrain can be limited by a smart welding strategy depicted in Figure 6. Patches, consisting of multiple layers can be welded with slopes on the sides where they have to be prolonged in order to form the desired structure. The slopes allow to connect a new patch to the previous patch. This strategy allows to move the chamber successively over the substrate and will be demonstrated in further investigations.

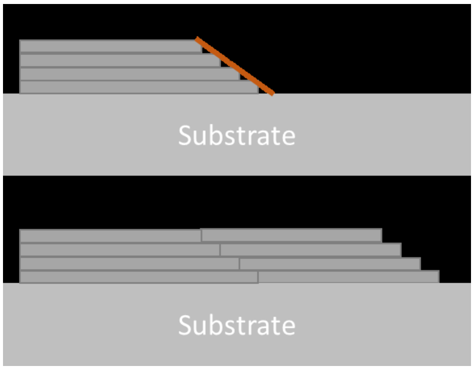

Figure 6: Patch based weld strategy

Acknowledgement

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