Laser beam welding of titanium additive manufactured parts

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Abstract

In this paper the joinability of titanium Additive Manufactured (AM) parts is explored. Keyhole welding, using a pulsed laser beam, of conventionally produced parts is compared to AM parts. Metal AM parts are notorious for having remaining porosities and other non-isotropic properties due to the layered manufacturing process. This study shows that due to these deficiencies more energy per unit weld length is required to obtain a similar keyhole geometry for titanium AM parts. It is also demonstrated that, with adjusted laser process parameters, good quality welds for aerospace applications in terms of pressure resistance and leak tightness are achievable.

1. Introduction

Additive Manufacturing (AM) is a relative new type of production technology. Parts are generally built using a layered approach, thus enabling the formation of part features that are impossible to produce using reductive manufacturing techniques (e.g. turning, milling, etc.). At first the AM of polymers was used predominantly to produce models for visual purposes. However as the processes are maturing and with the option to produce metals as well, AM is establishing itself as an advanced type of production technology and design engineers are increasingly embracing its unique properties to design parts with complex embedded functionalities.

In this paper, the joining process of titanium AM parts is investigated. Ideally all required features are integrated into one part; however, this is not always possible. For instance, due to the size of the build chamber, due to the fact that multiple features demand multiple part orientations or simply due to cost aspects. In such, and other cases, multiple parts may be produced that need to be joined as a secondary process step.

Metal AM processes typically use a laser beam as energy source to fuse particles together. This process is similar to the much researched process of Laser Beam Welding (LBW); the difference being the fusing of particles in a powder bed versus the fusing of a seam between typically two solid parts. The interaction of the fused and unfused particles in the powder bed and its effect on the mechanical properties of the final parts are still ill understood phenomena in the area of metal AM.

1.1. Research question

The main research question for this study is: Can we join titanium AM parts with similar process settings as LBW of conventional titanium parts?

It is well known that powder bed based laser beam AM processes (e.g. SLM, SLS, DMLS, laser cusing, etc.) typically do not reach full density. In this study, the effect of remaining porosities in the AM parts on the weldability is researched, as this is believed to have a negative influence. The weld characteristics and process settings for LBW of conventional parts and AM parts are compared.
The application of this research is primarily for butt welding for aerospace applications. This demands a pressure resistant hermetic weld that is 100% leak tight along the entire weld joint.

1.2. Research approach

To compare the weldability of conventional and AM parts, a test part is designed that is produced both conventionally (i.e. by turning) and by AM, in this case Selective Laser Melting (SLM). Titanium alloy Grade 5 (i.e. Ti6Al4V) is chosen as base material, because of its relative low density (low weight), corrosion resistance and good processability [1]. For aerospace applications Ti6Al4V is a very common alloy.

The test part is composed of essentially two cylindrical disks that are joined along the circumference, as shown in Figure 1. The outer diameter is 32mm. An internal cavity, connected through a connection tube, is inserted to test the pressure resistance and leak tightness of the weld connection. Also, thermocouples are attached along the bottom part to measure the amount of heat conducting into the part during the welding process.

For the AM parts, the build direction was vertically upwards with respect to Figure 1 in order to keep the connection tube circular. The AM parts for this study are produced using an SLM Solutions 280HL machine.

The pressure resistance and leak tightness of the weld joint and the accompanying part process temperature are critical for this study, as for the real application electronics are embedded into a pressurized part. Before welding the test part, a series of test welds are performed in a bead-on-plate configuration to find the best set of process parameters (i.e. laser power, pulse duration, pulse frequency and welding speed). Naturally, for the conventional test part a conventionally produced piece of material was used, and similarly for the AM test part an AM produced piece of material was used.

1.3. Outline

The paper is structured as follows. Chapter 2 gives a short literature background on metal AM. In Chapter 3 the process settings for keyhole welding using a pulsed laser are compared for convention and AM parts. Chapter 4 presents the application results and weld quality for the LBW of the test part of Figure 1 for aerospace applications. Finally, in Chapter 5 the conclusions of this study are presented.

2. Metal additive manufacturing

Powder bed based metal AM processes build a 3D structure in a layered approach. Features are produced by fusing raw material, a fine powder, layer by layer, stacking layers until the full 3D part is ready. This is illustrated in Figure 2. Loose powder is rolled from the powder supply side to the part build area. Here, the powder is fused where needed by the laser beam, using the part’s computer (CAD) model. After producing a layer, a new layer of loose powder is rolled onto the previous. This cycle continues until the complete (end-) part is produced.

Typically, AM parts are prone to small imperfections (e.g. remaining porosities) as shown in Figure 3, where cross-sections of SLM processed titanium are shown. Full density is usually not reached and parts are sensitive to non-isotropic behavior caused by the layered process and the subsequent build direction. Also, a relative high surface roughness compared to conventional manufacturing is common [3]. Surface roughness values (Rz) in the range of 10μm and higher are to be expected for titanium alloys [4]. As LBW requires a surface roughness of 1.6μm or better, in such cases the joining surfaces of the AM parts have to be post processed (e.g. by turning).

To reach full pressure resistance and 100% leak tightness of the welded test part itself, laser sintering is
not sufficient and laser melting is chosen as metal AM production technique. For this study, the SLM production process itself was not of prime interest, the resulting parts are however. Hence, for the part production standard machine vendor settings and powder were applied with the build direction as discussed in Section 1.2.

Fig. 3: Cross-sections of SLM processed titanium for various scan spaces and scan speeds [3].

3. Process settings for keyhole laser beam welding

3.1. Laser beam welding parameters

Three types of parameters are used when studying laser welding processes, namely quality parameters, workpiece parameters and process parameters.

Quality parameters for keyhole laser welding can be assessed by analyzing the geometry of the welded cross-section [5]. As keyhole welding occurs at high laser intensities, causing the material to evaporate locally [6], it forms a capillary filled with hot metal gas or plasma that can extend over the complete depth of the workpiece. This property allows high welding speeds with a small Heat Affected Zone (HAZ) and better mechanical properties.

The quality of keyhole welding processes can be assessed by the following parameters [7]:
- h1 representing the width of the HAZ
- h2 representing the penetration depth of the welding
- h3 representing the dimensions of underfill defects
- h4 representing the width of weld pool

These parameters are also shown in Figure 4.

Fig. 4: Keyhole geometry for pulsed laser beam welding [7].

The workpiece parameters are material properties, part thickness and the type of welding (e.g. overlap, butt-weld, etc.). The material properties are obviously very important for final weld quality; however, for AM parts these are not well predictable. This uncertainty is the subject of investigation of this research.

Important process parameters of pulsed laser welding applications are the laser power (P), the pulse time (t), the pulse frequency (f), welding speed (V), the shielding gas composition and gas speed [8]. As pulsed laser beam welding processes depend on the characteristics of the pulses, a typical parameter used to synthetize the process characteristic is the energy input per unit weld length. This energy input is determined as follows:

$$ E = \frac{P \cdot t \cdot f}{V} $$

In this study, good quality welds for conventional and AM parts in terms of keyhole geometry are studied by comparing the required energy input E.

3.2. Experimental results

For this research a commercially available Nd:YAG pulsed LBW apparatus is used with a spot size of 0.60mm and argon as a shielding gas. As discussed, the main process parameters that influence the weld quality are laser power P, pulse duration t, pulse frequency f and travel speed V. The shielding gas parameters were kept constant. The laser power and pulse duration determine the amount of energy that is put into the workpiece at each pulse. The pulse frequency and welding speed determine the pulse overlap. This overlap should be large enough to guarantee sufficient effective penetration [8] and thus a pressure resistant weld and leak tight seal. In this study an 80% pulse overlap is aimed for.

For both test parts (i.e. conventional and AM), first a number of beads is welded on a part of similar material properties. For each bead, the laser process settings are varied to estimate the right energy input per pulse (i.e. the combination of laser power and pulse duration) and to estimate the right pulse overlap (i.e. the combination of pulse frequency and travel speed).
The first indication of the weld quality was obtained by analyzing the top view of the weld. From this view the weld width and pulse overlap can be determined. Figure 5 shows the results of two tests where a bead was welded on conventional titanium. Figure 5(a) shows a poor weld quality attributed to the limited pulse overlap and ultimately resulting in a permeable joint. The weld quality of Figure 5(b) is much better with a measured distance of 0.23mm between the pulses, meaning a 62% overlap. As aforementioned, our design rule is to aim for an overlap of 80% to guarantee sufficient penetration. The width of the weld bead in this case was 0.60mm, which is identical to the laser spot size.

The second indication of the weld quality was obtained by analyzing the weld cross-section. From this view the weld depth and weld width (i.e. h2 and h4 of Figure 4) can be determined. The results of this experiment are presented in Table 1 for conventional titanium and Table 2 for AM titanium. In both tables the energy per unit weld length \( E \), according to Equation (1), is increased from left to right. An image of each cross-section is presented.

Fig. 5. Top view of weld beads on conventional titanium (Ti6Al4V).

Table 1. Keyhole dimensions for several laser process settings for conventional titanium (Ti6Al4V).

<table>
<thead>
<tr>
<th>Conv.</th>
<th>Laser power (W)</th>
<th>Pulse length (ms)</th>
<th>Energy (J/mm)</th>
<th>Depth (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>400</td>
<td>4</td>
<td>6.0</td>
<td>0.27</td>
<td>0.57</td>
</tr>
<tr>
<td>II</td>
<td>500</td>
<td>5</td>
<td>7.5</td>
<td>0.35</td>
<td>0.67</td>
</tr>
<tr>
<td>III</td>
<td>600</td>
<td>6</td>
<td>10.7</td>
<td>0.67</td>
<td>0.82</td>
</tr>
<tr>
<td>IV</td>
<td>700</td>
<td>7</td>
<td>18.3</td>
<td>0.75</td>
<td>1.10</td>
</tr>
<tr>
<td>V</td>
<td>800</td>
<td>8</td>
<td>23.9</td>
<td>0.91</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Table 2. Keyhole dimensions for several laser process settings for additive manufactured (SLM) titanium (Ti6Al4V).

<table>
<thead>
<tr>
<th>AM.</th>
<th>Laser power (W)</th>
<th>Pulse length (ms)</th>
<th>Energy (J/mm)</th>
<th>Depth (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>800</td>
<td>2</td>
<td>13.3</td>
<td>0.212</td>
<td>0.766</td>
</tr>
<tr>
<td>II</td>
<td>1000</td>
<td>2</td>
<td>16.7</td>
<td>0.392</td>
<td>0.845</td>
</tr>
<tr>
<td>III</td>
<td>800</td>
<td>3</td>
<td>20.0</td>
<td>0.600</td>
<td>0.952</td>
</tr>
<tr>
<td>IV</td>
<td>1000</td>
<td>3</td>
<td>25.0</td>
<td>0.718</td>
<td>1.068</td>
</tr>
</tbody>
</table>

Note that the scale is not the same for all images in Tables 1-2. The images show a typical keyhole geometry. Only the image of Conv. V in Table 1 shows a pore inside the keyhole, which is an indication of a poor weld quality due to too much energy input locally.
For each cross-section the settings for the laser power \( P \) and the pulse length \( t \) are given as well as the resulting laser energy per unit length \( E \). Finally, the measured weld depth and weld width are given. All keyholes are wider than their depth.

For both type of parts a similar (logical) trend can be observed, namely that for a higher energy input per unit weld length the keyhole dimensions grow. This is also illustrated in Figure 6. An interesting observation is that for the same energy per unit weld length the keyhole dimensions for an AM part are smaller than for a conventional part. The trends for both type of parts are very similar; there is however an offset. This effect is best explained by the material consistency and imperfections due to the AM process. As visible in Table 2, the AM parts have quite some remaining porosities, indicated by the black spots. Also, the grain structure of the material is very chaotic.

4. Laser beam welding of test parts

With the best laser process settings for conventional and AM separately, the test parts of Figure 1 were welded along the circumference. Welding was done with a stationary weld apparatus and a rotary table to rotate the test parts. This set-up is shown in Figure 7. Other welding parameters were kept constant and similar to the settings of Section 3.2. Also visible in the figure are the exit of the shielding gas from the left and eight thermocouples that are mounted inside the bottom half of the test part. With the thermocouples the heat penetration into the part was measured.

Figure 8 shows the final results of two of the welded test parts. Figure 8(a) shows the welded conventional titanium part and Figure 8(b) shows the welded AM titanium part.
As mentioned in Chapter 2, LBW requires a roughness of 1.6µm or better; hence, the weld areas of the AM test parts were post processed to make them smoother. Other areas were not treated, as can be observed from the surface textures in Figure 8(b).

In Figure 9 a 3D surface reconstruction of the AM part is shown to illustrate the surface roughness resulting from the powder bed based production process. The reconstructed surface represents a side view perpendicular to the part build direction. The measured surface roughness (Ra) values were 5.1µm and 4.6µm for the horizontal and vertical direction, respectively.

The sealing of both welds were leak tested using a helium mass spectrometer. Typically aerospace applications are required to have a leak rate of less than $5 \times 10^{-6}$ mbar·l/s to protect equipment from contamination [9]. In both cases, the weld had a leak rate smaller than $10^{-10}$ mbar·l/s. This value equals the upper detection limit of the mass spectrometer and indicates a (virtually) 100% leak tight seal. The welds were retested after pressurizing the cavity up to 60bar to test the pressure resistance. The integrity of the test parts was not compromised and they all remained 100% leak tight.

During the welding process the part temperature distribution was also monitored at several locations by the thermocouples. The temperature profiles inwards showed a linear declining trend indicating heat transfer by conduction. The temperature profiles for both type of parts were nearly identical. Hence the presence of the porosities in the AM part does not affect the conduction of heat on this small scale.

The maximum temperature at the first thermocouple location from the weld area (i.e. 1mm inwards) was $52^\circ$C for the conventional part and $51^\circ$C for the AM part. Both well below the allowed boundary for the aerospace electronics.

5. Conclusions

The quality of laser beam welding of titanium additive manufactured parts has been compared to the welding of conventionally produced parts. In particular titanium (Ti6Al4V) and keyhole welding using a pulsed laser source were examined. The keyhole geometry for different laser process parameters has been presented for both type of parts (i.e. conventional versus additive manufactured).

This study has demonstrated that laser beam welding process parameters cannot simply be transferred from conventional to additive manufactured parts. For the latter more laser induced energy per unit weld length should be used in order to obtain an identical weld geometry. The resulting weld is leak tight and pressure resistant. With respect to the internal part temperature distribution during the welding process, both type of parts do not differ significantly.

This study has also demonstrated that with an adjusted set of process parameters it is possible to hermetically weld additive manufactured parts together. Future research will address other weld quality parameters such as mechanical loading and the welding of two differently manufactured type of parts.

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