Studying the Application of Additive Manufacturing to Large Parts

Leonor Machado Santos Carvalho Neto
leonor.neto@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal
May 2017

Abstract

The full intake of Wire-Arc Additive Manufacturing (WAAM) for large aluminium aircraft components is hampered by the absence of deposition algorithms and variable mechanical properties of as-deposited aluminium. In this study, different intersection strategies were investigated. Single bead and multi-bead thick walls with various intersections were manufactured using AA4043 and AA2319 wires with Cold Metal Transfer processes. For thick wall intersections, two approaches were used, combination of parallel-oscillated deposition and combination of crossings with parallel deposition. The parallel-oscillated strategy was ultimately selected to manufacture the final part (6-metre long demonstrator). Two strengthening mechanism by cold work, side rolling and machine hammer peening (MHP), were investigated. A depth of porosity free zone, which varied from 0.6 to 1.85 mm depending on the material and peening density, was obtained in MHP samples. Side rolled samples exhibited a reduction of porosity only in narrow regions below the edges of the flat roller. After solution treatment and natural aging, a decrease in porosity was obtained, but after artificial aging gas pores reappeared. By applying heat treatment to AA2319 peened samples resulted in the abnormal grain growth. An increase of surface hardness by 50-70% was achieved by peening and 20% increase was achieved by side rolling with 150 kN load, as compared to as-deposited condition. The strength increased for peened and as-deposited and heat treated samples. The elongation considerably increased for peened and heat treated conditions. It has been shown that WAAM process is capable of manufacturing large aerospace components in aluminium alloys.

Keywords: Wire + Arc Additive Manufacturing (WAAM), aluminium alloy, intersections and cross-overs, cold work, machine hammer peening, side rolling

1. Introduction

With an ever-growing industrial competition, the need to reduce costs and optimize processes is in constant demand. Conventional processes, such as machining, consist of time consuming tasks and often lead to a high material waste. Additive manufacturing (AM) processes have proven to be a suitable solution. By manufacturing near-net shapes a reduction of material wastage is obtained and leading times of manufacturing are highly reduced [1,2].

As arc-based and wire-feed AM processes are associated with high deposition rates and large working envelops, the combination of an arc heat source and wire as the feedstock is the most suitable option for large component manufacturing. This option was named Wire plus Arc additive manufacturing (WAAM) by Cranfield University, one of the most active research institutes in AM technologies [1,3].

The capability of WAAM for high deposition has been demonstrated for several materials [1,4]. The initial research on AM was mainly focused on titanium and nickel alloys due to their high value and large waste in conventional manufacturing. However, after the discovery of precipitation hardened aluminium alloys, the aerospace industry showed a high interest in applying AM technology to aerospace parts. Aluminium alloys present a suitable compromise between weight and strength and, therefore, are used to replace other more expensive materials or where weight reduction is important. To satisfy the demands of the industry, the capability of WAAM to deposit aluminium alloys has to be further developed and features such as crossings and complex intersections established [4].

In applications of aluminium deposition, control of defects and material properties are the key to ensure good integrity of the part. The most common defect is porosity, which is caused by hydrogen entrapment in the deposited material. Hydrogen contamination is hard to control, since its main sources come from the ambient environment and is stored in the feedstock material, which is directly fed into the weld pool, and the substrate in which the material is deposited [5]. It was found that low heat input decreases the likelihood of porosity and, for this reason, new cold MIG processes, like Fronius CMT, started being a better option for aluminium [6].

To further reduce or even eliminate porosity, different options of cold work were studied. Cold work when applied in the form of inter-layer rolling
(every layer deposited) has proven to be an effective way of eliminating porosity in aluminium alloys [7,8]. This process although effective is not an efficient process. Since it needs to be applied in every layer, the process becomes time consuming and flattens the beads shape of the previous depositions, which requires deposition of additional layers to compensate for this. Thus, other rolling options, such as side rolling or pinch rolling can be applied on the final part after completion of the deposition. This can offer a significant reduction in manufacturing time and hence make the process more economic. However, the capability of these processes to reduce porosity has not been proven yet [9]. Nevertheless, these processes can only be applied on simple geometries, which limits their usefulness in real applications.

Machine hammer peening is a relatively new process, which offers greater flexibility than rolling, since potentially it can be applied on any geometry, and also it does not require heavy load gantry system. Other peening variants have proven to be effective in the reduction of surface corrosion, fatigue crack initiation and porosity, but no details on application of this technology for AM parts have been reported [10-12].

Most aerospace grade alloys are used for engineering applications only in the heat-treated stage. To prove usefulness of machine hammer peening on aluminium alloys, first its effect on the material after various heat treatments needs to be understood. At certain point, the enhancement of mechanical properties induced by cold work may decrease and reopening of porosity may occur. For this reason, to obtain a sound part with good mechanical properties a combination of the deposition and cold work processes with appropriate heat treatment should be applied [7,8,12].

In this paper, different deposition strategies for crossings of single beads and thick walls were investigated, with the aim to build the part in Figure 1. To guarantee the deposition of a sound aluminium part with good mechanical properties, different cold work methods were considered. As it is not economically viable to apply interlayer rolling to large components, side rolling and machine hammer peening were tested and their impact in mechanical properties and porosity was accessed. To further improve the quality of the material different heat treatments were applied and its effect in combination with cold work determined.

2. Experimental and Methods
2.1. Material

Four different materials were used for the deposition of single bead crossings, hybrid crossings, single bead wall and parallel wall, with the chemical compositions presented in Table 1 – Chemical Composition of all used Aluminium Alloys. For the single bead crossings, the substrates had dimensions of 250x65x12mm of Aluminium Alloy 6082-T6 (AA6082-T6). The same material was used for hybrid crossings, but the test substrate had dimensions of 500x300x22mm. The deposited material used was 1.2mm diameter wire of Aluminium Alloy 4043 (AA4043). For the application of cold work, besides the combination of materials previously presented, Aluminium

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Chemical Composition [%wt.]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
</tr>
<tr>
<td>6082-T6</td>
<td>0.7-1.3</td>
</tr>
<tr>
<td>4043</td>
<td>4.5-6.0</td>
</tr>
<tr>
<td>2024</td>
<td>0.50</td>
</tr>
<tr>
<td>2319</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Figure 1 – Preliminary 6 metre long aerospace part

Table 1 – Chemical Composition of all used Aluminium Alloys
Alloy 2319 (AA2319) wire and Aluminium Alloy 2024 (AA224) substrate were used for single bead and parallel walls. The geometry of the base plates was identical to the one used for single bead crossings.

2.2. Equipment

A 6-axis KUKA robot was used for all depositions with a CMT welding power source incorporated. CMT Pulse (CMT-P) and CMT Advanced Pulse (CMT-PADV) processes were used for deposition. The shielding gas was pure argon (99.99%) with a flow rate of 25 l/min and the contact tip to work distance (CTWD) was kept at 13 mm. A standard welding MIG torch was used with incorporated shielding. Single bead and parallel walls were deposited in a static working table. The experimental trials of hybrid crossings were performed on a support frame for large components and integrated in a rotation table.

For Machine Hammer Peening, a FORGEfix (Air) pneumatic tool was installed on a second KUKA robot. Cold Rolling was performed using a hydraulic rolling rig. The rolling equipment consisted of a roller and hydraulic piston, which applies the force required for cold work. A flat roller of H13 steel with a diameter of 100 mm and 20 mm width was used.

2.3. Methodology

2.3.1. Deposition

To be able to deposit a large scale industrial part, it was assumed that the best approach would be to deposit a long wall consisting of shorter intersecting sections, rather than building it in one go. Two different strategies for intersections, curved link and opposite angles 2 strategy (adapted from 13) were used, which are presented in Figure 2 and Figure 3, respectively.

For the curved link intersection, the overlap (33.66 and 80%) and radius (9.6 or 20 mm) were changed throughout the experiments. The process used was CMT-PADV and an end length of 30 mm was considered. For the second option, two processes, CMT-P and CMT-PADV, were tested. The integrity of the parts, level of defects and accuracy of deposition shape were accessed.

To achieve thicker wall crossings, additional strategies were investigated: crossing and parallel deposition strategy and parallel and oscillated deposition strategy.

The first approach is the combination of single bead crossing and parallel wall technologies, as presented in Figure 4. Radius, wire feed speed (WFS) and centre beads distance were the main variables studied. The second approach was the combination of parallel wall and oscillated strategy, as presented in Figure 5. The oscillated wall path was produced by an oscillated movement of the torch and the main variables were the centre distance between the longer parallel beads and the perpendicular distance between them and the WFS. In these cases, the accuracy, integrity and level of defects was also accessed.

2.3.2. Machine Hammer Peening

Machine Hammer Peening (MHP) was studied to improve the mechanical properties and reduce porosity. Single and parallel walls were built in AA219 and AA4043 and the side of the walls was machined to achieve flat surfaces on which peening was applied. The tool was operated at a constant pressure of 5 bar and frequency of
approximately 250 Hz. A cylindrical pin with a round end of 8 mm diameter was used.

The peening density (P. density) was varied by changing the travel seed (TS), line pitch (s) and displacement (d), as shown in Table 2.

Table 2 – Peening conditions

<table>
<thead>
<tr>
<th>TS [mm/s]</th>
<th>s [mm]</th>
<th>d [mm]</th>
<th>Peening density [hits/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>0.3</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>0.15</td>
<td>22</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>0.10</td>
<td>33</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>25</td>
<td>0.1</td>
<td>–</td>
<td>100</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>0.15</td>
<td>22</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>0.10</td>
<td>33</td>
</tr>
</tbody>
</table>

2.3.3. Side Rolling

Side rolling was also studied as an alternative method of improving mechanical properties and reducing porosity. Walls in AA4043 were machined, positioned in a flat orientation and clamped prior to rolling. The roller was positioned at a distance of 5 mm from the wall edge and lowered until in contact with the wall. Then compressive force was applied to its surface by the hydraulic cylinder and the roller. The rolling process started with a speed of 600 mm/min and a load of 75 kN. After rolling a length of 30 mm, the process was terminated. This procedure was repeated in another part of the same sample with an increased load of 150 kN.

2.3.4. Heat treatment

For AA2319 heat treatment was applied. Solution treatment at 535ºC for 120 minutes was firstly applied, followed by artificial aging at 175ºC for 360 minutes, as shown in Figure 6. Some samples, were additionally subjected to 3 weeks of natural aging between solution treatment and artificial aging.

Figure 6 – Temperature profiles of two cycle heat treatment implemented in AA2319

The effect of cold work in microstructure and reduction of porosity was accessed indirectly from macrographs. The depth of porosity free zone was determined by taking 15 measurements along the band near the MHP surface, until encountered a gas pore with a diameter higher than 20 µm. For side rolling only 3 measurements were taken.

Hardness was also measured. A Zwick/Roell ZHV hardness machine with a load of 100g and a dwell time of 15 seconds was used. Tensile tests of as deposited, as deposited and heat treated, peened, peened and heat treated conditions were tested. For the peened samples, a density of 25his/mm² was used. Three vertical and horizontal tensile test samples were extracted.

3. Main Results and Discussion

3.1. Crossings

3.1.1. Single bead crossings

To attain a long straight wall deposition, various strategies of robot and substrate movement were investigated considering that the maximum reach of each robot was only 2.5 metres.

Figure 7 shows an example of crossing. The effective wall width (EWW) and total wall width (TWW) are indicated. The variable A was added to describe also the effective wall width of the crossings. All the cases studied are presented in Table 3. In all cases, the difference between the values of TWW and EWW, which corresponds to the material to be machined, is small. Comparing cases 1 and 2, the increase in overlap does not influence significantly EWW and TWW. However, when the radius was increased, the EWW and TWW decreased, which can be attributed to strong attraction of the molten metal by adjacent bead, due to surface tension. The longer the contact between the beads (bigger radius), stronger the attraction. In all the first three cases, when using CMT-PADV, the EWW was in the order of 4 mm and, only by changing the process to CMT-P, a EWW of 6mm could be achieved.

Figure 7 – Transverse and longitudinal sections of crossing 1 from Table 3

Table 3 – Parameters used to study single wall crossings

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CMT-PADV</td>
<td>9.6</td>
<td>66</td>
<td>3.7</td>
<td>3.1</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>CMT-PADV</td>
<td>9.6</td>
<td>80</td>
<td>4.5</td>
<td>3.6</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>CMT-PADV</td>
<td>20</td>
<td>66</td>
<td>2.9</td>
<td>2.7</td>
<td>4.2</td>
</tr>
<tr>
<td>4</td>
<td>CMT-P</td>
<td>Opp. Angles</td>
<td>2</td>
<td>6.9</td>
<td>6.4</td>
<td>7.3</td>
</tr>
</tbody>
</table>
In single wall deposition, the dimensions of a wall are purely dependent of the volume of deposited metal and the surface tension-thermal balance. In the crossing where two walls merge together, additional effects related to the contact between the walls, wetting, surface tension and cooling effect of the previously deposited wall influence the wall height and width. Once the walls merge together, rapid cooling increases surface tension force and the resulting lateral depression of the beads can consequently narrow the crossing deposition. Since CMT-PADV has a narrow shape and a high bead height, its surface tension is higher than in the other processes. This effect of surface tension highly influences the connection between both beads. Similar findings were found in the literature [14,15]. As CMT-P has a higher heat input the wetting between the beads is smoother and in this way the effective wall width is similar to the values for singles beads. The narrowing due to surface tension is less significant in hotter processes, which is consistent with the results shown in the literature [16,17].

3.1.2. Hybrid crossings

As parallel wall deposition relies on deposition of multiple walls adjacent to one another with a defined overlap, this technique should be easy to apply to the single wall crossings. Thus, the combination of crossing and parallel walls was studied.

Table 4 summarizes the experimental parameters used. To manage the heat sink effect and control dimensions of the beads, the wire feed speed was changed between the layers until steady-state conditions. In the first trial, the difference between the exterior beads and the centre of each layer was very significant, indicated by the height difference. The best results in terms of smallest difference in height between different beads in each layer were achieved in trial 4, where radius and wire feed speed were varied between interior and exterior beads of each layer and a greater bead distance was used.

The variation of radius and WFS in each layer has proven to be an effective way of managing the heat and layer dimensions, hence reducing the height difference and producing more even depositions. Considering the height difference presented in Table 4, EWW and TWW values ranged from 21 to 22 mm and 31 and 32 mm respectively. These 10mm difference between the EWW and TWW, would cause a considerable material wastage for a large part. For this reason, a compromise between the height and width of be machined has to be accessed in order to optimize material wastage. Nevertheless, a sound structure was produced and the capability of this strategy was proved.

The main advantage of this approach is the uniform heat sink at the connection. However, it is more complex at programming stage, since there are many start and stop points required to complete a part.

Another way of achieving wider walls is the combination of parallel and oscillated strategies. As shown Figure 9 and Figure 10, this approach provides a better control of the total width of the wall. There is a significant height difference between the intersection and the outer features (Figure 10). To mitigate this difference, a dynamic control of TS or WFS could be potentially used. This strategy also requires less start and stop points. Therefore, there is a lower likelihood of defects as compared with the crossing and parallel deposition strategy.

<table>
<thead>
<tr>
<th>Radius [mm]</th>
<th>WFS [m/min]</th>
<th>Bead distance [mm]</th>
<th>Height difference [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 R2 R3</td>
<td>1st Layer</td>
<td>2nd Layer</td>
<td>3rd Layer</td>
</tr>
<tr>
<td></td>
<td>Centre</td>
<td>Ext.</td>
<td>Centre</td>
</tr>
<tr>
<td>1</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4 – Parameters used to study crossing and parallel deposition strategy

Figure 8 – Crossing and parallel deposition strategy (case 1 from Table 4)
3.2. Machine Hammer Peening

With the goal to improve the mechanical properties of aluminium, machine hammer peening (MPH) was applied to the sides of deposited walls of AA2319 and AA4043.

3.2.1. Effect on porosity

Figure 11 presents the deformation (X) and depth of porosity free zone (Y) for the as deposited and peened condition (P+AD). All data for this and other heat treatment (HT) conditions, such as solution treatment and natural aging (P+ST+NA) followed by artificial ageing (P+ST+NA+AA), are summarized in Table 5.

For all AA2319 samples, the deformation was almost constant having a slight increase in samples where a second and third tool pass with offset of the MHP tool was applied. This suggests that the deformation in multi-pass processing is more effective in increasing the depth of cold work in the material than the peening density in a single pass. This may be attributed to the distribution of peened spots. A constant offset between each pass resulted in more even distribution of compressive strain than overlapping. With displacement, the peening is not applied always in the same place and in this way the surface is more evenly flattened with an increase of deformation.

For AA2319 P+AD condition, the lowest depth of porosity free zone is associated with the lowest peening density. However, the values for the remaining samples are very similar to each other. This is in disagreement with Kirk [18] who showed that the layer of compressed depth increased with increasing peening intensity. Moreover, the reduction in porosity can be explained by annihilation of pores by compressive stresses and deformation. It has been shown in the literature, Toda et al. [12] that at least 50% of local compressive strain is needed for effective annihilation of pores. This implies that the peening strategy and distribution of strain field should have an important effect on mitigation of porosity. It has also been shown [12] that in some cases the compressive stress field is not homogenous. Some regions were exposed to tension and others to a variable compressive strain. However, in the region right after the peened surface, a high percentage compressive strain seems to be evenly applied. The increase of overlap during peening increases the likelihood of more homogeneous distribution of compressive stress. Most likely the compressed surface layer increases with the increase of peening density, but the response is not linear, which means that at a certain depth the strain is not uniform and thus the annihilation of micro pores is less effective.

For the P+ST+NA condition, the depth of porosity-free zone increased to an average of 1.10 mm depth. This can be explained by reorientation of grains during heat treatment. During peening, pores are disintegrated into micro pores, which are stored mainly around dislocation, in interstitial lattices and grain boundaries [12,19]. There is a direct link between the microstructure and porosity.

Table 5 – Extent of deformation and porosity free zone

<table>
<thead>
<tr>
<th>Density [hits/mm²]</th>
<th>Deformation (X) [mm]</th>
<th>Depth of porosity free zone (Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 2319</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>22 (m.p.a.)*</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>35 (m.p.a.)*</td>
<td>0.27</td>
<td>0.15</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>22 (m.p.a.)*</td>
<td>0.32</td>
<td>1.02</td>
</tr>
<tr>
<td>35 (m.p.a.)*</td>
<td>0.35</td>
<td>1.69</td>
</tr>
</tbody>
</table>

*multi pass peening

In Figure 12, microstructure of as deposited and peened sample is shown. This is compared with Figure 13, which presents P+ST+NA condition. There is a clear boundary in the microstructure after the exposure to high temperature. This can be explained by the compressive strain that was applied by peening and the rearrangement of grains. Thus, the porosity the interstitial lattices and grain boundaries was relocated and, in this case,
possibly trapped in this boundary, once it has similar depth as the free porosity zone.

For the P+ST+NA+AA condition, the depth of porosity free zone decreased considerably, achieving lower values than for the AD condition. This suggests that further exposure to high temperature lead to the re-opening of crushed and/or annihilated pores. Toda et al. [12] presented a similar result when applying peening to an aluminium alloy and subsequently heat treating it. For non-annihilated pores the exposure to a higher temperature can cause their growth and porosity merges due to the Ostwald effect.

3.2.2. Effect on Microstructure

The deformation for AA4043 increases with the increase in peening density in a coherent way. The AA4043 P+AD case has an increase of depth of porosity free zone with an increase of peening density, as described by Kirk [18]. Similar to the AA2319 P+AD condition, for the samples with multi-pass peening a higher increase in peening depth was observed. This reinforces the notion that the peening pattern highly influences the depth of porosity free zone. Also, as AA4043 is a softer material than AA2319, the microstructural resistance to cold deformation is lower and thus the impact in porosity increases.

3.2.3. Effect on Micro-hardness

Figure 14 summarizes the micro-hardness results for the AA2319 sample peened with 25 hits/mm² in P+AD, P+ST+NA and P+ST+NA+AA conditions. Similar results were obtained for remaining peening densities.

Comparing the values of the P+AD bulk average and the P+ST+NA+AA condition, an improvement of approximately 110% was achieved for the later. However, when comparing the same condition with the P+AD near the surface, this increases only approximately 35%. From all the results presented, the P+ST+NA+AA condition presents the highest improvement in hardness. However, as this improvement is independent of the peening effect, no peening would be required to achieve these results. When P+ST+NA+AA or P+ST+NA cannot be applied to the part for dimensional or practical reasons, peening presents a considerable superficial hardness improvement.

Figure 15 presents the micro-hardness of AA4043 for different peening densities. As A4043 is a less resistant to dislocations and material deformation, the peening affects much greater depth and the thickness of the region with increased hardness is much greater, as compared to AA2319. Also, for this material, the influence of peening density on the hardness is much lower, which suggests that significant improvement of hardness can be obtained for a smaller peening densities.
3.2.4. Tensile Properties

In Figure 16, tensile properties of samples in AA2319 for as deposited, after peening and different HT conditions are compared.

For the non-peened or as-deposited samples, the values of ultimate tensile strength (UTS) and proof strength (PS) are similar for both directions. When peening is applied, the UTS and PS values increase when compared with AD, but the elongation decreases. As the increase of material strength is due to the increase in density of dislocations and deformation of the material, the mobility of the dislocations is constrained. In this way, the ductility of the material is compromised and thus the elongation decreases.

When HT is applied to the AD material, the UTS and PS values increase. For the heat treated peened specimens, the UTS and PS values obtained are lower than the ones for the peened samples without HT and AD with HT. The values obtained do not represent the strength drop characteristic for the grain growth behaviour. However, the elongation increase, particularly when compared with the AD_{HT} condition, suggests exactly what is expected in the grain growth situation.

3.3. Side Rolling

Side rolling was also used as an alternative way of improving mechanical properties and reducing porosity.

3.3.1. Effect on Porosity

Figure 16 presents a narrow and deep porosity free zone near the edge of the roller. This observation implies that only in the corner of the flat roller, enough strain was induced to eliminate porosity. As explained earlier, the porosity annihilation is highly dependable on the applied strain during cold work. Only for a compressive strain of 50% or higher, the elimination of porosity occurs. Neves et al. [21] reported a strain distribution for cold-forged parts. A much higher strain was recorded for the region that was in the contact with the edge of the plunger compared to region that was in contact with the central part of the tool. Most likely, a similar situation is occurring during the application of the flat roller in the WAAM deposited wall. Only the corners of this tool apply enough compressive strain for the annihilation of porosity and in the rest of the material the strain is more evenly distributed and material uniformly compressed without significant effect on porosity. Also, the deformation and depth of porosity free zone increase with increasing the load, as shown in Table 6.

3.3.2. Effect on Microstructure

In Figure 18, the microstructure directly under the edge of the roller, for the applied load of 150 kN, is presented. A superficial refinement of grains caused by the flat roller was obtained, presented as Zone A. Zone B represent an incoherent grain structure, which is characteristic for the arc based deposition of AA4043 [22]. This confirms that...
much higher strain was induced near the edge of the roller than in the middle of the roller. Very similar results were obtained for an applied load of 75 kN, but with a smaller Zone A. This proves that the increase in rolling load increases plastic deformation.

Figure 18 – Microstructure near the edge of the roller

3.3.3. Effect on Micro-hardness

Figure 19 presents the micro-hardness results measured from the surface to a depth of 6mm for the sample side rolled with 75 and 150 kN. The improvement obtained for a load of 75 kN was not considerable. There is scatter of the data for this load and the average micro-hardness is almost the same as the bulk average. However, when the load was increased to 150 kN, an overall increase in hardness was obtained. Comparing with the bulk average results, micro-hardness was increased by approximately 20%. The same trend was found in another work with the application of inter-layer rolling in AA2319. [8]

Figure 19 – Micro-hardness measurements for AA 4043 rolled with two different loads

When comparing micro-hardness for MHP (Figure 15) and side rolling (Figure 19), a completely different behaviour can be observed. The micro-hardness enhancement for peening is only considerable near the surface, whereas side rolling presented a throughout improvement. But the maximum value near the surface is much higher for peening. This suggests that peening applies more concentrated effect, rolling in contrast, applies more uniform but over greater depth change of properties. For this reason, MHP should be applied to walls with approximately 1mm thickness or in cases where only superficial improvement is required. Side rolling does not reach such a high micro-hardness near the surface but it offers homogenous micro-hardness improvement in the examined thickness, which proves its capability for deeper improvement.

4. Conclusions

During this study, the capability of large scale AM deposition strategies was proven. Considering the need to improve the mechanical properties of the deposited material, two cold work options were applied and analysed. The following conclusions can be drawn from this work:

- Single bead crossings for aluminium were deposited successfully with different overlaps.
- To obtain the least possible material wastage, curved links in the crossing intersection were successfully connected with no visible defects using CMT-PA process.
- By applying the opposite angles 2 strategy, crossing of single beads using CMT-P were successfully manufactured.
- For thick wall crossings, two reliable strategies were developed by combining parallel strategy with single bead crossings, and parallel with oscillated strategies.
- It was proven that by applying machine hammer peening to the side of already deposited material, a porosity free zone was obtained for considerably low deformation.
- It was found that the depth of porosity free zone increases with increasing peening density, i.e., by increasing overlap or by applying multi-pass. However, these results were dependent on the material. For AA2319, this zone increased after solution treatment and natural aging but after applying artificial aging porosity reappeared, due to the high temperature exposure.
- Regarding the microstructure of AA2319, as-deposited peened samples showed fine and equiaxed grains but after heat treatment an abnormal grain growth developed. This was caused by the material flow and high temperature exposure of the compressive strained material.
- An increase of hardness after peening or rolling was found. For as deposited peened samples, an improvement of 50% for AA2319 and 70% AA4043 was obtained, when comparing with the bulk average. After performing artificial aging, a similar trend for peened and non-peened samples values was obtained.
- For side rolling, an overall hardness improvement of 20% was obtained for the sample with an applied load of 150kN, but for 75kN no significant improvements were achieved.
- In conclusion, peening is suitable for a superficial hardness improvement, whereas rolling applies an overall increase of hardness.
• It was proven that by applying peening and heat treatment the ratio of strength to elongation can be controlled.
• The strength improved considerably for as-deposited and heat treated samples as well as peened. The elongation increased considerably for the peened and heat treated conditions.

5. Acknowledgments

I am grateful to all the members of the Welding Engineering and Laser Processing Centre at Cranfield University and Instituto Superior Técnico for the support and motivation. This work was supported by the WAAMMat programme and its industry partners.

6. References