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Influence of interlayer temperature on microstructure of 5183 aluminium alloy made by wire arc additive manufacturing

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Abstract: The variations in mechanical properties compared to the traditional processed (wrought) products, porosity formation, and solidification cracking are the primary concerns that may restrict industrial applications of wire arc additive manufacturing (WAAM) aluminium alloy products. Interlayer temperature is one of the crucial factors that can adversely affect the built quality and properties of material produced using WAAM. The paper aims at the possible effects of different interlayer temperatures on the geometry and microstructure of WAAM aluminium 5183 alloy as a function of varying heat input. For a given heat input, samples built using a higher interlayer temperature (100°C) showed wider and shorter layer deposits with increased penetration compared with lower interlayer temperature (50°C) samples. Microstructure of the chosen material revealed columnar grains at each layer and equiaxed grains at layer overlap position and at top layer. Interlayer temperature had a minor influence on deposit geometry and microstructure.

Keywords: WAAM; wire arc additive manufacturing; aluminium; interlayer temperature; microstructure; layer geometry.


Biographical notes: Karan S. Derekar is a PhD student at Faculty of Engineering, Environment and Computing of Coventry University, UK working on materials properties after wire arc additive manufacturing. He received his Bachelor’s degree in Metallurgical Engineering and Master’s in Welding Technology. He was a Welding Engineer for three years in pressure vessel manufacturing industry and later lecturer for more than two years before pursuing his PhD. He is a Member of The Welding Institute. He is currently based at National structural Integrity Research Centre (NSIRC), Cambridge, UK. He is interested in metallurgy and materials properties associated with metal additive manufacturing.

David Griffiths is a metallurgist specialising in the metallurgy of components produced by additive manufacturing (AM) technologies including selective laser melting (SLM), wire plus arc AM (WAAM) and laser metal deposition (LMD). He was awarded a PhD from Manchester University for his work on improving the formability of rare earth containing magnesium alloys. Since completing his PhD, he joined TWI and now has experience in evaluating the properties of AM materials including strength, toughness and corrosion resistance of materials including 316L stainless steel, nickel Alloys 625 and 718 and Ti-6Al-4V deposited by a range of AM processes.

Sameehan S. Joshi completed his PhD in Materials Science and Engineering from University of North Texas in 2017 where he analysed laser processing of
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Jonathan Lawrence is Academic Research Director of Manufacturing in the Institute for Future Transport and Cities, and heads up the Manufacturing and Materials Engineering Division. He has been active in laser materials processing and associated fields of research for almost 25 years. His main research contribution has been in the area of laser surface engineering science and technology, with particular emphasis on using lasers for wettability characteristics modification, improving the biocompatibility of materials and laser shock peening (LSP). He has also developed new science and approaches to bonding and welding of a wide range of materials, as well as a technique for the laser ignition of gas turbines. He has presented and published widely in these areas – with eight books, 10 book chapters and over 150 international journal papers. His work has yielded six patents relating to the novel use of lasers and laser materials processing. His research has attracted funding from bodies such as EPSRC, DTI, Innovate UK, Advanced Propulsion Centre (APC), BEIS, international government sources, and national and international industry; amounting to over £5 million since 2001, £2.3 million since 2014. Recent and current work has involved the H1PERBAT – High Performance Battery Pilot Facility and Optipress – Stepped Change in Precision and Strength Optimisation Capability for Steel Fabrications. He is an Editor-in-Chief of Lasers in Engineering and the International Journal of Laser Science: Fundamental Theory and Analytical Methods. He serves on the editorial boards of three international academic journals and is a Steering Committee Member for the Association of Industrial Laser Users (AILU).

Xiang Zhang studied Aeronautical Engineering at Northwestern Polytechnical University in China (MSc) and aerostructures at Imperial College London (PhD). In her academic career, she has worked for three Universities in the UK: Imperial College for seven years as Research Associate; Cranfield University for 18 years with Senior Lecturer and Readership appointments; currently at Coventry University as a Professor in Structural Integrity since 2015. Professional status: Fellow of the Royal Aeronautical Society; Chartered Engineer.

Adrian Addison is a Mechanical and Manufacturing Engineer. Starting as a machine shop apprentice, he spent 15 years as a CNC machine programmer, setter and operator, manufacturing critical parts from exotic materials for several industry sectors including aerospace, automotive and defence. He joined TWI’s friction group in 2000 and has run research and development projects in rotary, stud, plug, linear, and friction stir welding, ranging from fundamental research to application into series production. 2011–2013 were spent in the automotive industry developing and applying to production the joining technologies for a high end aluminium body in white. After this, he returned to research for wire and arc additive manufacturing, helping to develop the WAAM process and supporting technology with an industrial mind-set, and supporting the development of best practice guides, conformance AQ2: Please reduce career history of no more than 100 words for the author 'Jonathan Lawrence'
practices and controlling standards with the aim of seeing the process adopted by industry.

Geoff Melton is Technology Manager and Joining Programme Manager at TWI Ltd. He has been employed previously at a number of welding equipment and consumable manufacturers in technical support, development and managerial roles. He has spent his career working on a wide range of projects relating to the development and application of welding process technology. His particular areas of expertise are in arc welding process and equipment development, monitoring, health and safety, robotics and automation. His recent projects involve process automation and robotics in the aerospace, automotive and heavy construction industries for a range of materials including steels, aluminium, titanium and nickel superalloys. He has authored of over 20 papers on welding technology. Geoff is the Chairman of the International Institute of Welding (IIW) C VIII on Health Safety and the Environment and is a UK delegate to IIW.

Lei Xu is a Senior Project Leader in the Arc Process, Fabrication and Welding Engineering Section at TWI Ltd. He graduated with a BE in Mechanical Engineering and followed this with an MSc in Manufacturing Systems and a PhD on Robotic Arc Welding. He is a Chartered Engineer and a Member of both the Welding Institute and the Institute of Mechanical Engineers. His main experiences are in robotic arc welding and additive manufacturing for aerospace, power generation, rail, automotive, construction and other industry sectors, involving a range of materials such as aluminium, carbon and stainless steels, titanium and nickel. He has led R&D projects developing robotic TIG welding, PAW, MIG/MAG welding, process monitoring and measurements of residual stress in welded structures. He has authored and co-authored over 10 journal and conference papers on welding and additive manufacturing.

This paper is a revised and expanded version of a paper entitled [title] presented at [name, location and date of conference].

1 Introduction

High material efficiency, high deposition rate, potentially no dimensional limitations during part production, and good manufacturing flexibility are the advantages of the wire arc additive manufacturing (WAAM) technique (Derekar, 2018). Applicability of WAAM for the manufacturing of low to medium complexity parts with medium to large size (Williams et al., 2016) has made it a promising technique.

Widespread use of aluminium alloys in the aerospace and other sectors has triggered interest into the application of components produced through WAAM (Derekar, 2018). However, for WAAM processed aluminium alloys, imperfections such as porosity (Gu et al., 2016), solidification cracking (Horgar et al., 2018) and reduced strength compared to the wrought products (Fang et al., 2018) are the critical factors restricting its applications. Implementation of controlled dip metal transfer technique, for example Fronius cold metal transfer (CMT) and interlayer rolling as a set of post processing methods has been reported to achieve substantial reduction and in some cases complete elimination of porosity in finished WAAM (Gu et al., 2016). At the same time, to minimise the requirement of post processing, it is important to develop an understanding
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about influence of processing parameters on formation of defects and development of microstructure in WAAM material.

WAAM has evolved from the conventional arc welding technique. Control of the interpass temperature has always been one of the crucial practical factors in welding. The adverse effect of welding on hardness of 7xxx aluminium alloy plates at high interpass temperatures has been discussed (Kou, 2003). Also, the author mentioned, to avoid hydrogen cracking in alloy steels interpass temperature is one of the controlling parameters. The microstructure of a formed object through layer deposition has been discussed in details by many researchers. Zhang et al. (2018) studied the effect of variable polarity CMT on microstructure and mechanical properties of aluminium alloy. In another approach, Zhang et al. (2019) studied the effect of work piece vibration on microstructure and mechanical properties. However, the specific interlayer temperature (temperature of a layer immediately before deposition of successive layer) and its impact on material properties have not been reported in open literature. The term interlayer temperature referred to here is similar to the interpass temperature in a welding operation. The temperature of a top layer of an additively manufactured part immediately before the deposition of a successive layer is considered as the interlayer temperature. While depositing an object, focus is usually put on the inter layer waiting time as discussed by Gu et al. (2016) and Gomez Ortega et al. (2018) through robotic programming instead the temperature of previously deposited layer prior to deposition of successive layer. Deposition of metal in a layer type format with fixed time interval gradually raises the temperature (Wu et al., 2017) of a forming object. This leads to an increase in interlayer temperature as the layer building progresses. In an attempt to reduce the effect of temperature built up, heat removal techniques and heat sink effects were explored by Xiong et al. (2018) and Wu et al. (2018). Geng et al. (2017a) reported improved, consistent and smooth layer appearance to be undulated surface by increasing the interlayer temperature from 50°C to 120°C. Their findings suggested that the bead geometry was unacceptable when interlayer temperature went over 150°C. The results are in agreement with BS EN 1011-4:2000, which is an arc welding standard for welding aluminium alloys that suggests a maximum interpass temperature of 120°C for similar filler wire chemistry.

Microstructural features, in particular crystallographic texture and grain orientation show a great influence on the strength of an additively manufactured aluminium part. Evolution of grain orientation heavily depends on the metal deposition direction. Geng et al. (2017b) discussed anisotropy in tensile properties when applied tensile load was parallel and perpendicular to the grain orientation. Moreover, processing parameters such as heat input and interlayer temperature are expected to further affect microstructure evolution in WAAM material.

There is a limited published literature in the field related to effects of interlayer temperature. In light of this, the present investigation attempts to explore the influence of interlayer temperature on the layer geometry and microstructure evolution of 5183 aluminium alloy produced by pulsed metal inert gas (MIG) variety of WAAM.
2 Methods and materials

2.1 Filler material

Commercially available ER5183 aluminium solid wire of 1.2 mm diameter was selected as a filler material for the study. Chemical composition of the filler wire is given in Table 1. A substrate of comparable chemistry with dimensions of 500 × 250 × 20 mm was used during the deposition experiments described in the following subsection.

| Table 1 Chemical composition (wt%) of filler wire ER5183 |
| Si | Mn | Cr | Cu | Ti | Fe | Mg | Zn | Be | Al |
| 0.06 | 0.65 | 0.07 | 0.01 | 0.07 | 0.14 | 4.91 | < 0.01 | 0.0002 | Balance |

2.2 Part deposition using WAAM

WAAM samples were manufactured using direct current (DC) pulsed metal inert gas (MIG) process. OTC Welbee P500L power source integrated with OTC robotic arc was used for the part manufacture. Overall equipment set up employed for the WAAM process is illustrated in Figure 1.

Figure 1 OTC equipment and overall set up employed for WAAM structure deposition (see online version for colours)

OTC designed inbuilt software was used to produce a suitable program in order to deposit the selected filler wire in a layer by layer manner. Details of the process parameters deployed for the part deposition are detailed in Table 2. For schematic of WAAM operation refer Figure 2. Step shaped component was manufactured by depositing a total of five layers in a manner that microscopic samples can be extracted from each layer starting from Layer 1 to Layer 5 separately (see Figure 3). Two such parts were built by maintaining two different interlayer temperatures namely 50°C and 100°C alternatively using high heat input (0.327 kJ/mm) and the process was repeated with low heat input.
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(0.157 kJ/mm) (refer Table 2 for more details). Thus, total four stepped components were manufactured. The same temperature was also maintained at the substrate during the deposition of the first layer by applying 50°C or 100°C preheat for the respective specimens. Figure 3 shows typical shape of a manufactured part. The weld pool was shielded through the torch using pure argon gas (99.997%) with a gas flow rate of 25 l/min.

Table 2  Details of pulsed MIG process parameters used for building WAAM parts

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High heat input</td>
</tr>
<tr>
<td>Base current (A)</td>
<td>70</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>300</td>
</tr>
<tr>
<td>Wave frequency (Hz)</td>
<td>240</td>
</tr>
<tr>
<td>Linear torch travel speed (m/min)</td>
<td>0.6</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>19</td>
</tr>
<tr>
<td>Wire feed speed (m/min)</td>
<td>8.65</td>
</tr>
<tr>
<td>Wire feed speed to torch travel speed ratio (WFS/TS)</td>
<td>14.4</td>
</tr>
<tr>
<td>Heat input (J/mm)</td>
<td>327</td>
</tr>
</tbody>
</table>

Figure 2  Schematic of typical WAAM process
A contact type thermometer was used for the measurement of surface temperature of each layer before deposition of successive layer. As discussed earlier, BS EN 1011-4:2000 restricts the maximum welding interpass temperature to 120°C for a similar wire chemistry used in the current study. Therefore, a maximum temperature of 100°C was chosen for the experimentation. Considering the productivity of the process, thus, interlayer waiting/dwell time between the two depositing successive layers, could be too long to reduce the temperature of deposit to room temperature. Hence, an intermediate temperature of 50°C was chosen as the lower bound in interlayer temperature during current investigation.

2.3 Sample nomenclature

In further discussion within the manuscript, samples manufactured with high heat input are identified by letter ‘H’ while samples with low heat input will be named using letter ‘L’. The number before the identification letter represents the number of layers whereas, the number after the identification letter provides the interlayer temperature. For example, Sample 1H50 and 1H100 would represent a step of the component with only one layer manufactured with high heat input and 50°C and 100°C interlayer temperature respectively, Samples 2L50 and 2L100 would represent two layered component manufactured using low heat input and 50 and 100°C interlayer temperature respectively. Continuing on these lines, 5H50 and 5H100 denotes samples with total five layers manufactured using high heat input and 50 and 100°C interlayer temperature respectively.

2.4 Macro and micro scale examination

Samples were extracted from each layer of the deposited part for macro and micro scale observations. After cutting samples to a suitable shape, all samples were cold mounted.
using MetPrep made Quick-set cold mounting powder and liquid following standard metallography procedure. Mounted samples were polished on polishing papers with grades ranging from 120, 320, 600, 1200–2500 successively. The polishing operation was performed under constant running water. Samples, were further polished on lapping wheel using lubricating agent having diamond suspended particles of size 3 µm, 1 µm and 0.25 µm sequentially. Optical microscopy was used for macro scale study and measurements. Layer height and width were measured for each mounted specimen using a software package from Leica – LAS v4.4. Measurements of geometric parameters are described in Figure 4. Selected specimens were carefully etched using Baker’s reagent (6% Fluoboric acid in water) for 2 min. Microstructural examination was performed on polarised microscope using Leica software. Standard line intercept method following ASTM E112-13 was used to determine the average grain size. Overall structure and procedure followed in this study can be seen in Figure 5 considering variables such as consumable, process employed and processing conditions including interlayer temperature and heat input as an input variables and macro and micro observations are output.

Figure 4  Schematic of WAAM depicting dimensional measurements followed in this study

3 Results and discussion

3.1 Layer geometry

The high heat input samples showed the total height difference of 0.37 mm and the difference in widths was 0.89 mm (Figure 6(a) and (b)) for low and high interlayer temperature samples. In case of low heat input samples, the difference observed was
0.26 mm in height and 0.25 mm (Figure 7(a) and (b)) in widths for low and high interlayer temperature samples. The samples manufactured with 50°C interlayer temperature showed greater height in both high and low heat input processed samples compared to 100°C interlayer temperature samples. However, samples with processed 100°C interlayer temperature showed increased width compared to 50°C interlayer temperature. Measurements of height and widths were performed as mentioned in Figure 4 for all the samples.

Figure 5  Block diagram explaining overall structure and procedure followed in this study (see online version for colours)

Figure 6  Macrographs of samples 2H50 (a) and 2H100 (b) comparing geometrical features (see online version for colours)
Effect of interlayer temperature on the part and layer geometry manufactured with high and low heat input is illustrated in Figures 8 and 9 respectively. It is apparent from Figure 8 that there is only a small difference in height and width between the two different interlayer temperature values while comparing the same layer number. For Samples 5H50 and 5H100, the difference in height and width was around 9% and 7%. The graph highlights the fact that all the samples manufactured with 50°C interlayer temperature revealed increased total height and reduced layer width compared to the samples deposited with 100°C interlayer temperature. Also, despite the small magnitude of the differences in height and width, the graph demonstrates an increasing trend of the height to width ratio (H/W ratio) for all samples manufactured with high heat input. Comparing the effect of interlayer temperature, it was observed that for all the samples, H/W ratio of the samples prepared using 50°C interlayer temperature was higher than samples manufactured with 100°C interlayer temperature for respective layer numbers. It was concluded that the higher interlayer temperature reduced sample height which was compensated by increment in sample width. Thus, samples manufactured with 50°C interlayer temperature were thinner and higher than samples with 100°C interlayer temperature.

In case of low heat input samples (refer Figure 9), only marginal difference in the sample geometry (height and width) between the two different interlayer temperatures were observed. However, the overall trend of height and width variation as a function of interlayer temperature was not different from high heat input samples as discussed earlier. Unexpectedly, graph revealed Sample 5L100 higher than Sample 5L50 with marginal difference of 0.167mm while Sample 4L50 was wider than Sample 4L100 by 0.09 mm. Heat input also found to have influence on height and width of a deposit (refer Figure 10). From the graph, it can be inferred that high heat input samples revealed increase height and width compared to low heat input samples. The expected results highlights the fact that although the wire feed speed was raised approximately double from low to high heat input (Table 1), layer height and width could not be increased in the same proportion.
Figure 8 Effect of interlayer temperature on build geometry as a function of increasing layer numbers for high heat input samples (see online version for colours)

Figure 9 Effect of interlayer temperature on build geometry as a function of increasing layer numbers for low heat input samples (see online version for colours)

Comparative study of all four sets of samples with respect to layer geometry and height to width ratio (H/W ratio) is shown in Figure 10. As discussed earlier, distinctive trend can be seen for each set of sample. Increasing height and width in Figure 10(a) indicates increasing number of layers from 1 to 5. From Figure 10(a), it is clear that high heat input and 100°C interlayer temperature combination showed widest layers and low heat input with 50°C interlayer temperature had least wide layers. Also, high heat input samples showed relatively wider and taller layers than low heat input samples for all cases considered. Comparing high and low heat input samples, there was marginal difference in layer heights, however, difference in widths was considerably high. Effect of interlayer temperature on high heat input samples was prominent compared to low heat input samples. This can be attributed to the more amount of liquid metal deposition in high heat
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input mode compared to low heat input. High interlayer temperature supports in larger expansion and wider spread of aluminium than low interlayer temperature condition. Following Figure 10(b) that clearly reflects the results from Figure 10(a), confirming widest layer had lowest height to width ratio. Whereas, least heat condition, low heat input and low interlayer temperature, showed highest height to width ratio confirming a condition for depositing the least wide layer. Effect of interlayer temperature and heat input on the penetration is illustrated in Figure 11. Thus, the processing parameters significantly affected the build characteristics. Moreover, evolution of microstructure in the layered build was investigated as described in the following subsection.

Figure 10 Comparison of an effect of interlayer temperature and heat input on height and width (a) and height to width ratio (H/W ratio) (b) of all four sets of samples (see online version for colours)

3.2 Microstructures

3.2.1 Microstructure of single layer sample (Samples 1L50, 1L100, 1H50 and 1H100)

Micrographs obtained from the polarised microscope revealed columnar grains in the penetration region. The length of the columnar grains was found to have direct relation
with the depth of penetration. As shown in Figures 12 and 13, high heat input samples showed greater penetration that resulted into formation of longer columnar grains compared to lower heat input samples. Although, temperature of the substrate was maintained at 50°C and 100°C, due to rapid heat dissipation, corresponding rapid reduction in temperature could have initiated columnar grains in the penetration area of a substrate. Such a development of columnar grain growth at faster cooling conditions has been reported before by Kou (2003).

**Figure 11** Effect of heat input and interlayer temperature on penetration at the substrate (see online version for colours)

![Effect of interlayer temperature on penetration at the substrate](image1)

**Figure 12** Microstructures showing columnar grains in the penetration area of high heat input (327 J/mm) samples 1H50 (a) and 1H100 (b) (see online version for colours)

![Microstructures showing columnar grains](image2)

The area immediately above the columnar grains as shown in Figure 13 (i.e., deposit part above the substrate level) displayed equiaxed grain structure. Refer Figures 15 and 16 for high and low heat input micrograph samples respectively. The difference of 10.3 µm (51.5%) and 2.3 (15.7%) µm in the grain size can be observed in the micrographs Figures 14(a), (b) and 15(a), (b), respectively that highlights the effect of interlayer temperature on grain size. Smaller grains were observed in the samples prepared using 50°C interlayer temperature shown in Figure 14(a) (20 µm) and 14(a) (15.15 µm)
Influence of interlayer temperature on microstructure of 5183 aluminium alloy compared to samples manufactured with 100°C interlayer temperature displayed in Figure 15(b) (30.3 μm) and 15(b) (17.54 μm) respectively. Thus, the grain size from Figure 13(a) was 32% greater than Figure 15(a) and grain size in Figure 14(b) was 72.7% larger than in Figure 15(b). As discussed earlier for single layer sample, heat extraction by a substrate provided accelerated cooling for the liquid metal that could have forced the formation of elongated grains. The metal immediately above the penetration area on the top of substrate cools comparatively slower which can be identified from the presence of roughly equiaxed grains. The heat dissipation to the air and surrounding as well as to the substrate imparted multi-directional cooling.

**Figure 13** Microstructures showing columnar grains in the penetration area of low heat input (157 J/mm) samples 1L50 (a) and 1L100 (b) (see online version for colours)

![Microstructure of low heat input samples](image1)

(a) 1L50 (b) 1L100

**Figure 14** Illustration of an approximate location of microstructure graphs of single layer samples displayed in Figures 15 and 16 (see online version for colours)

![Illustration of microstructure graphs](image2)

**3.2.2 Microstructure of multi-layer sample with five layers (Samples 5L50, 5L100, 5H50 and 5H100)**

In multilayer deposition of five layers, vertical columnar grains are observed within every layer. Elongated grains, shown in Figures 18 and 19, were observed at layer 3 in low and high heat input samples irrespective of the interlayer temperature. Columnar grains are
found to be present throughout the layer thickness, however, they did not grow through layer boundaries as evidenced from Figure 17(a) and (b) and also Figure 18(a) and (b). Fine equiaxed grains were observed in the interlayer region along with porosity that can be seen in Figures 17 and 18 as highlighted within yellow coloured lines. These fine equiaxed grains are noticeably smaller than the equiaxed grains observed in the top layer of all deposits. It is also notable that columnar grains do not grow continuously through many layers of the deposit as WAAM or powder bed fusion of Ti-6Al-4V show prior beta grains which grow through many layers of the deposit (Ho et al., 2019).

**Figure 15** Microstructure graphs illustrating equiaxed grains at the location shown in Figure 15 in high heat input (327 J/mm) sample 1H50 (a) and 1H100 (b) (see online version for colours)

![Figure 15](image1)

**Figure 16** Microstructure graphs illustrating equiaxed grains at the location shown in Figure 15 in low heat input (127 J/mm) sample 1L50 (a) and 1L100 (b) (see online version for colours)

![Figure 16](image2)

The presence of columnar grains highlighted the temperature gradient and heat extraction direction i.e., heat extraction from the top layer to substrate. Comparing micrograph Figures 17(a) and 18(a) with micrograph Figures 17(b) and 18(b), the effect of higher interlayer temperature was more pronounced. The average lengths of grains in micrograph Figures 17(b) and 18(b) were longer than the average lengths of grains in micrographs Figures 17(a) and 18(b).
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Figure 17  Microstructure graphs showing elongated columnar grains at layer 3 along with the presence of fine grains and porosity at interlayer region of high heat input (327 J/mm) sample 5H50 (a) and 5H100 (b) (see online version for colours)

Figure 18  Microstructure graphs showing elongated columnar grains at layer 3 along with the presence of fine grains and porosity at interlayer region of low heat input (157 J/mm) sample 5L50 (a) and 5L100 (b) (see online version for colours)

A different microstructure was found at the top layer of the samples 5H50, 5H100, 5L50 and 5L100 as shown in Figures 19 and 20. The top layer of the samples illustrated equiaxed grains that were randomly oriented as shown in micrographs. A presence of dendritic structure within the equiaxed grains can clearly be seen. Top layer, the most inhomogeneous layer with as solidified structure, is the only one which does not undergo reheating and thus, does not have a change to homogenise with the deposited structure having columnar grains. It is evident from the micrographs that grains from the 50°C interlayer temperature processed samples namely 5H50 and 5L50 were smaller (55.55 µm and 35.7 µm respectively) in size compared to the samples 5L100 and 5H100 (71.42 µm and 37.03 µm respectively) built with 100°C interlayer temperature. The difference was about 28.5% and 3.7% respectively showing effect of interlayer temperature. Further, comparing the effect of heat input on grain sizes for the Samples 5H50 and 5L50 showed a difference of 55.4% while it was 92.8% for Samples 5H100 and 5L100. The difference between the melting temperature and interlayer temperature...
for samples built with 50°C and 100°C interlayer temperature is 588 and 538°C respectively. Hence, faster solidification is expected in sample with 50°C interlayer temperature which produced relatively smaller grains.

Figure 19  Microstructure graphs of top layer of sample 5H50 (a) and sample 5H100 manufactured with high heat input (327 J/mm) (see online version for colours)

![Microstructure graphs of top layer of sample 5H50 (a) and sample 5H100 manufactured with high heat input (327 J/mm).](image)

Figure 20  Microstructure graphs of the top layer of Sample 5L50 (a) and Sample 5L100 manufactured with low heat input (157 J/mm)

![Microstructure graphs of the top layer of Sample 5L50 (a) and Sample 5L100 manufactured with low heat input (157 J/mm).](image)

3.3 Further discussion

Geometry variation of the order of 0.5 mm was observed as a result of effect of change of interlayer temperature. This marginal variation within the heights and widths could be considered within experimental error, however, a consistency in the dimensional change could be drawn out following a trend throughout the geometry of a deposit. It could be inferred that to produce thicker sections higher interlayer temperature can be applied while lower interlayer temperature results in thinner and taller deposit. Further investigation regarding its effect on large structures could potentially reveal appreciable differences in the dimensions. Greater penetration observed at higher interlayer temperature reduced layer height within the multilayer specimen and thus increased the width. Metal remains more viscous due to faster cooling rate in the samples manufactured with 50°C interlayer temperature that allows comparatively lesser time to spread, forming
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a thinner deposit compared to less viscous metal in samples manufactured using 100°C that allows slower solidification process hence greater time to spread forming wider structure.

Microstructures of the studied samples showed similar grain structure irrespective of a layer numbers. Columnar grains within the layer and small equiaxed grains at interlayer region found consistent throughout the WAAM structure irrespective of layer temperature, heat input and position in the deposit. The top layer of each deposit showed large equiaxed grains with dendritic features. The dendritic grains witnessed differences in the size depending upon respective interlayer temperature as well as heat input, however, considering the product development and final shape of a component, the top layer is not of a great importance as such layers are often removed in final machining. Equiaxed grain structure at the top completely reforms into a columnar structure after deposition of successive layer. The heat from the arc, presence of liquid metal at the top and penetration effect of the arc could be considered responsible for the destruction of the equiaxed grains. The formation of equiaxed/columnar grains in the melt pool is a function of solidification rate and thermal gradient. These parameters vary at the top and bottom of the melt pool at each layer. Equiaxed solidification is favoured at the top of the melt pool in all cases with columnar growth at the bottom. As further layers are deposited the equiaxed grains are remelted leaving the columnar structure. The mechanism of formation of small equiaxed grains within interlayer region cannot be same as top layer. Also, small equiaxed grains cannot have come from large equiaxed grains. Formation of equiaxed small grains at the interlayer region and columnar grains through layer thickness of the WAAM processed aluminium samples needs further investigation. The related investigations will be a part of further study in continuation of the present paper.

It can be concluded that the process window of 50°C does not appreciably alter the microstructure. In a robotic metal deposition, time difference between two successive layers can be adjusted such that the interlayer temperature does not exceed 100°C to obtain fairly consistent microstructure. Thus, to expedite the production rate and for better efficiency of the process low interlayer dwell time can be applied. Operating window of 50°C does not appreciably alter macro as well as microstructure, resulting into a robust and stable process for the selected process parameters with pulsed MIG variety of the WAAM.

4 Conclusions

The interlayer temperature maintenance approach was explored for WAAM of aluminium – a different approach of metal deposition that was not widely considered before. Based on the presented results, following conclusions can be drawn:

- Samples prepared with 100°C interlayer temperature showed wider and shorter layer deposits with increased penetration compared to 50°C interlayer temperature samples. It was reflected into height to width ratio irrespective of layer number and heat input.
- Substrate penetration and thickness of layer evidenced columnar grains parallel to metal deposition direction.
• Interlayer region predominantly showed fine equiaxed grains irrespective of heat input and interlayer temperature.
• In multilayer deposition, top layer always showed equiaxed grains having smaller size for 50°C and larger for 100°C interlayer temperature.
• Operating window of 50°C does not appreciably alter deposit geometry as well as microstructure resulting into a robust process for chosen processing parameters.

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