Effects of Processing Parameters on Wire Arc Additive Manufactured Inconel® 718

This research also studied the geometry impacts on physical characterizations, microstructure, and mechanical properties

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ABSTRACT

The wire arc additive manufacturing (WAAM) process has demonstrated the potential to produce large parts with enhanced strength properties. This process is cost-efficient though challenging. In this research, the WAAM process was used to produce Inconel 718 parts. An investigation of the process parameters’ impact on the mechanical properties and geometric characterization of the parts was conducted. In addition, the microstructure was evaluated to analyze the solid-state phase evolution and intermetallics formation. The results showed that the size of intermetallics was different in the inner-layer and inter-layer regions of the WAAM part. The overall properties of the parts with diverse parameters indicated a small range variation. The WAAM material showed a lower strength in the layer direction than in the build direction due to grain growth orientation.

KEYWORDS

• Wire Arc Additive Manufacturing (WAAM) • Inconel 718
• Gas Metal Arc Welding (GMAW) • Mechanical Properties • Intermetallics

Introduction

In recent years, additive manufacturing (AM) processes are proposed for rapid production and direct manufacturing of parts by adding materials to achieve the final shape. Direct energy deposition (DED) approaches are proven, cost-effective AM methods to fabricate large metallic parts. The DED process involves a feedstock (powder or wire) and a focused thermal energy source that melts the recently built material layer as the subsequent layer is deposited (Ref. 1). Wire arc additive manufacturing (WAAM) is a DED technique using wire as the feedstock and an arc as the heat source. The arc can be produced by traditional welding methods, including gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma (Ref. 2). In the GMAW process, the wire plays the role of both consumable and electrode. This coaxial movement makes an easier path to create a geometry (Ref. 3).

Inconel 718 is a Ni-based superalloy with high strength and excellent creep resistance at elevated temperatures with myriad applications in aerospace and petrochemical industries (Ref. 4). The high strength, hardness, and toughness make the fabrication of Inconel 718 parts very challenging during conventional manufacturing processes, such as subtractive methods. AM offers reductions in material waste and tooling costs by fabricating a part directly. The WAAM process is capable of producing Inconel 718 parts with high productivity and fewer defects, such as porosity, compared to powder-based additive manufacturing techniques (Ref. 5).

The AM part has an anisotropic microstructure and resultant mechanical properties compared to the wrought material. The microstructural characteristics depend on the local cooling rate and thermal gradient resulting from the fabrication process and parameters. Although there are many studies on the microstructural and mechanical properties of the AM Inconel 718 under various DED process conditions (Ref. 6), the parametric research using the GMAW-based WAAM methods remains limited. Clark et al. evaluated shaped metal deposition (SMD) as a commercial process to build aero-engine components made of Inconel 718 (Ref. 7). Delta (δ) and laves phases, which have detrimental effects on the mechanical life of the part, were observed in the as-deposited material. Xu et al. used two different GMAW wires with a slight difference in the chemical composition to manufacture WAAM Inconel 718 wall structures (Ref. 5). They considered the existence of oxide and their composition as two variables. In addition, the mechanical properties after solution + aged heat treatment were compared with the as-built materials. Xu et al. introduced a new modified heat treatment for WAAM postprocessing, which meets minimum specifications for conventional cast material (Ref. 8). In this method, laves phase was almost fully dissolved without precipitating δ phase, unlike conventional heat-treatment methods.

This study investigates the microstructure, solidification structure, and associated mechanical properties of WAAM Inconel 718 thin structures. These parts contain four walls...
and one tube build by the GMAW equipment. The component’s configuration, shielding gas, deposition direction, and interlayer idle time (IIT) are the effective parameters considered in this parametric study. The results show the effect of these parameters on the final shape and associated mechanical properties of the WAAM product.

**Experimental Procedures**

**Materials and Experimental Setups**

The material used as the substrate for all of the WAAM components was A36 steel in the as-received condition with dimensions of $250 \times 75 \times 6$ mm. The 0.035-in. (0.9-mm) ERNiFeCr2 Inconel 718 was used as the GMAW wire. The wire composition was determined using energy dispersive spectroscopy (EDS) analysis. The material compositions are given in Table 1. The WAAM operation was carried out using a semiautomatic method. In this method, a motor controls the gun travel speed, and the height is adjusted by a threaded adjustment rod. Figure 1 shows the schematic illustration and the experimental setups for the fabrication of the walls and the tube. The threaded rod plays the role of a central axis rotated by the motor as shown in Fig. 1A. The gun is fixed to a radius adjuster locked by a pin to the rod. The rotation of the rod pushes the gun upward adjusting the height while deposition occurs. In the wall setup (Fig. 1B), the motor rotates a gear engaging with a threaded guide along the deposition direction. The height of the gun is adjusted after each layer deposition by a handle attached to a threaded rod.

**Table 1 — Chemical Composition of the Used Materials (wt-%)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>Si</th>
<th>Ti</th>
<th>S</th>
<th>P</th>
<th>Cu</th>
<th>Mn</th>
<th>C</th>
<th>Al</th>
<th>Co</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate (A36 steel)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.28</td>
<td>—</td>
<td>0.05</td>
<td>0.04</td>
<td>0.20</td>
<td>1.03</td>
<td>0.25</td>
<td>—</td>
<td>—</td>
<td>98</td>
</tr>
<tr>
<td>Wire (Inconel 718)</td>
<td>52.8</td>
<td>18.5</td>
<td>1.86</td>
<td>3.18</td>
<td>0.76</td>
<td>0.99</td>
<td>0.00</td>
<td>0.00</td>
<td>0.19</td>
<td>0.11</td>
<td>0.08*</td>
<td>0.57</td>
<td>0.00</td>
<td>21.0</td>
</tr>
</tbody>
</table>

*Carbon was not included in the measurement and the value is provided by the vendor (Ref. 9).

**WAAM Process**

For the parametric study, one tube and four linear thin-wall components were deposited. Each component contains 30 layers. The processing parameters are listed in Table 2. The temperature was measured using thermocouples attached on the top surface of the substrates at a distance of 12 mm from the weld center. The thermal data of wall I is unavailable. The measured thermal cycles are shown in Fig. 2. The IIT is the time delay before starting the deposition of the subsequent layer on the former built layer. The IIT influences the interlayer temperature leading a different microstructure in the WAAM part. The interlayer temperature was not measured in this study because of resource limitations. The IIT was only considered for manufacturing the walls; however, the tube layers were deposited continuously in a counterclockwise (CCW) direction without IIT. Argon was selected as the shielding gas for the fabrication of the tube and three walls, and helium was used for the manufacturing of one wall (wall I). The IIT impact on the properties of the WAAM material was studied by prototyping walls II and III that the IIT was reduced from 60 to 20 s. In another trial, the deposition strategy was investigated to understand the influence of the deposition path on the microstructural development in the WAAM process (wall IV). In this trial, other manufacturing parameters were reserved as the same as ones for producing wall II. It should be noted that the bidirectional deposition path (walls I, II, and III) means that the initial point of the subsequent layer was the end of the formerly built layer. In the unidirectional deposition strate-
Metallurgical Preparation and Analysis

For microstructural evaluation, the central sections of the walls and tube along the layer direction were selected to be sectioned. The metallographic samples are illustrated in Figs. 4 and 5. The samples were sectioned using a water jet cutting device, ground using abrasive papers, polished, and etched using 6 mL HNO₃ + 6 mL HCl + 3 mL glycerol to reveal the microstructure. The microstructure was observed by optical microscopy (OM) followed by scanning electron microscopy (SEM). The chemical composition was measured by EDS analysis.

Mechanical Testing Procedure

The polished samples underwent a microhardness test. The measurements were performed using a Vickers hardness tester under a load of 500 g with the settling time of 10 s.

In this study, a miniature tensile specimen was designed, as illustrated in Fig. 3. The specimen shape was selected based on the ASTM E8 standard. To avoid stress concentration, an FE analysis was performed on the miniature configuration using COMSOL Multiphysics®. During the analysis, various values of gage length, width, and the curve radius in the gauge section were examined until the final optimum geometry was obtained (Ref. 10).

Ten tensile specimens were extracted out of each wall along with the vertical and horizontal directions, five specimens in each direction as shown in Fig. 4. The horizontal and vertical directions are referred to as the layer and build directions, respectively. Furthermore, five vertical specimens were extracted from the tube as presented in Fig. 5. The samples were mechanically mirror polished and then etched to track the fracture location. An in-situ optical microscope was used to monitor the deformation during the tensile test.

Results

WAAM Components’ Geometry

Four walls and one tube were prototyped. The ultimate geometries of these WAAM products are shown in Fig. 6, and the associated size is given in Table 3. Wall I was observed to be the tallest and thinnest among the walls. In the case of IIT reduction, wall III is the shortest and widest (width of the layers). Interestingly, the geometries of walls II and IV were the same and hence, it can be concluded that the path strategy did not affect the WAAM parts’ geometry. However, the parts’ distortion was different in wall II from
Wall IV due to a different distribution of residual stresses, which is out of the scope of the current study.

**Microstructure Evaluation**

To compare the effect of process parameters on the solidification morphology, the microstructures of longitudinal sections were revealed as indicated in Figs. 4 and 5. The solidification morphology of the WAAM components in the longitudinal direction is shown in Fig. 7. In each subfigure, two optical images were vertically stitched, as indicated by the dark blue arrow. The dotted lines are sketched to specify the inter-layer region between two deposited layers. The inter-layer is the region remelted from the former layer during the deposition of the subsequent layer. As seen in Fig. 7, the columnar dendrites were extended from the layers’ interface toward the top of the subsequent layer in the direction of the heat flow.

The inter-layer region contains a finer solidification morphology than the inner-layer zone. The columnar solidification, which is the common morphology in all of the WAAM products, is coarser in the inner-layer of the tube (see tube in Fig. 7) due to a lower cooling rate during the continuous deposition implying an IIT of zero. Helium shielding gas used in wall I enhances the temperature gradient during the deposition process (Ref. 11). As a result, the finest columnar is evident in wall I due to a higher temperature gradient resulting in an elevated cooling rate. It should be noted that the WAAM process is the high-power deposition technique. In such depositions, the grains grow vertically and independently of the deposition direction (Ref. 12) as is evident in Fig. 7 for wall IV.

The microstructure of the inter-layer and inner-layer regions of the WAAM components are shown in Fig. 8. White arrows point to the columnar dendrites and black ones indicate the intermetallics. As shown in the optical images, coarser intermetallics were present in the inner-layer regions of the WAAM products than in the inter-layer zones. By comparing the inner-layer and inter-layer regions of WAAM components, the microstructure of the walls was found almost similar, indicating that the processing parameters, such as type of shielding gas, IIT variation from 20 to 60 s, and deposition strategy had little impact on the microstructural evolution. The optical

<table>
<thead>
<tr>
<th>Product</th>
<th>Avg. Diameter (mm)</th>
<th>Avg. Length (mm)</th>
<th>Avg. Layer Width (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube</td>
<td>95</td>
<td>—</td>
<td>11</td>
<td>52</td>
</tr>
<tr>
<td>Wall I</td>
<td>—</td>
<td>210</td>
<td>6</td>
<td>46</td>
</tr>
<tr>
<td>Wall II</td>
<td>—</td>
<td>210</td>
<td>8</td>
<td>38</td>
</tr>
<tr>
<td>Wall III</td>
<td>—</td>
<td>210</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td>Wall IV</td>
<td>—</td>
<td>230</td>
<td>8</td>
<td>37</td>
</tr>
</tbody>
</table>
image for the tube in Fig. 8 represents larger dendrite cores and intermetallics in both the inter-layer and inner-layer regions in the tube. This observation reveals that the microstructural evolution occurred under different thermal conditions during the building processes of the tube and walls. Two thermal models developed by Hejripour et al. (Ref. 13) showed different thermal distributions for those structures during the WAAM process.

To compare more details of the walls’ microstructure with the tube, the SEM images of the tube and wall II are indicated in Fig. 9. The SEM results in different regions (inner-layer and inter-layer) of layers 15 and 16 were investigated. The arrows indicate various phases, intermetallics, and the composition corresponding to the arrows’ color, which is provided in Table 4. It can be seen that the columnar cores and arms are larger in the tube. In the inter-layer region, the dispersed laves phases have a larger size in the tube compared to the wall due to different heat distribution in these WAAM structures. The microscale carbides and nanoscale γ’ disperse all over the matrix. There was no δ phase detected in the matrix of the tube and the wall by SEM investigation at high magnifications. The austenitic dendrite core contains the lowest Nb content where the solute is rejected into the primary phase (L). The partition coefficient (the ratio of Nb concentration in solid and liquid phases at the solid/liquid interface) in this region is about 0.5 calculated from the EDS

![Image](image.png)

**Fig. 7 — Solidification morphology of the WAAM components between layers 14 and 15. The location shown by the dark blue arrow is the interface between two attached micrographs.**

<table>
<thead>
<tr>
<th>Arrow Color Code</th>
<th>Phase/Intermetallic</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>Cr</th>
<th>Fe</th>
<th>Ni</th>
<th>Nb</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Laves</td>
<td>0.24</td>
<td>0.86</td>
<td>1.23</td>
<td>12.35</td>
<td>Bal.</td>
<td>45.91</td>
<td>20.81</td>
<td>4.74</td>
</tr>
<tr>
<td>White</td>
<td>TiN</td>
<td>1.50</td>
<td>0.07</td>
<td>66.45</td>
<td>2.45</td>
<td>Bal.</td>
<td>4.24</td>
<td>29.08</td>
<td>2.17</td>
</tr>
<tr>
<td>Red</td>
<td>NbC</td>
<td>0.20</td>
<td>0.00</td>
<td>20.01</td>
<td>2.29</td>
<td>Bal.</td>
<td>4.47</td>
<td>65.97</td>
<td>4.71</td>
</tr>
<tr>
<td>Blue</td>
<td>γ’</td>
<td>0.38</td>
<td>2.38</td>
<td>1.22</td>
<td>16.05</td>
<td>Bal.</td>
<td>46.82</td>
<td>12.91</td>
<td>3.52</td>
</tr>
<tr>
<td>Brown</td>
<td>Nb-rich</td>
<td>0.41</td>
<td>0.52</td>
<td>1.96</td>
<td>12.96</td>
<td>Bal.</td>
<td>52.58</td>
<td>14.41</td>
<td>3.20</td>
</tr>
<tr>
<td>Yellow</td>
<td>Dendrite core</td>
<td>0.53</td>
<td>0.29</td>
<td>0.67</td>
<td>18.54</td>
<td>Bal.</td>
<td>52.39</td>
<td>2.46</td>
<td>2.69</td>
</tr>
<tr>
<td>Green</td>
<td>L</td>
<td>0.38</td>
<td>0.31</td>
<td>0.79</td>
<td>17.79</td>
<td>Bal.</td>
<td>52.40</td>
<td>4.23</td>
<td>3.10</td>
</tr>
</tbody>
</table>

*Table 4 — The Chemical Composition of Primary Phases and Intermetallics Shown in Fig. 9 (wt-%)*

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MARCH 2021 / WELDING JOURNAL 97-s
measurements, resulting in relative high segregation of Nb in the layers. Interestingly, a uniform dispersed distribution of inclusions is also observed in the matrix. These inclusions are identified as nitrides and oxides, as presented in Fig. 10. These inclusions act as nucleation sites for carbides (NbC, TiC) detrimentally impacting mechanical properties, such as tensile strength (Ref. 5). The chemical composition of the inclusions and nucleated carbides are given in Table 5.

**Mechanical Properties**

The microhardness test was performed on the central line of the WAAM component’s cross section. The microhardness distribution along the build direction is shown in Fig. 11. The horizontal axis shows the distance of the indentation from the fusion boundary of the first layer with the substrate. The fluctuation is due to placing indentations at

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**Table 5 — The Chemical Composition of the Inclusions Shown in Fig. 10 (wt-%)**

<table>
<thead>
<tr>
<th>Point</th>
<th>Intermetallic</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>Cr</th>
<th>Fe</th>
<th>Ni</th>
<th>Nb</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alumina (Al₂O₃)</td>
<td>33.23</td>
<td>0.00</td>
<td>44.69</td>
<td>0.90</td>
<td>Bal.</td>
<td>2.34</td>
<td>17.18</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>Al, Ti-rich</td>
<td>17.06</td>
<td>0.00</td>
<td>10.34</td>
<td>14.77</td>
<td>15.83</td>
<td>33.70</td>
<td>5.76</td>
<td>2.53</td>
</tr>
<tr>
<td>3</td>
<td>TiC</td>
<td>0.00</td>
<td>193</td>
<td>0.16</td>
<td>82.50</td>
<td>0.72</td>
<td>10.89</td>
<td>13.79</td>
<td>11.51</td>
</tr>
<tr>
<td>4</td>
<td>TiN</td>
<td>0.13</td>
<td>0.05</td>
<td>47.19</td>
<td>1.02</td>
<td>0.73</td>
<td>1.63</td>
<td>43.40</td>
<td>2.70</td>
</tr>
<tr>
<td>5</td>
<td>NbC</td>
<td>0.00</td>
<td>0.00</td>
<td>10.75</td>
<td>1.91</td>
<td>1.72</td>
<td>3.43</td>
<td>77.66</td>
<td>4.53</td>
</tr>
</tbody>
</table>
different regions, such as inner-layer and inter-layer zones. The hardness variation lies within the range of 260–370 for all of the WAAM products. Also, it is seen that the microhardness of the upper layers dropped compared to the hardness of the middle layers in each WAAM component.

The microhardness of indentations shown in Fig. 11 were averaged for each WAAM product and compared in Fig. 12. It can be seen that the average microhardness of wall III is 10 HV higher compared to the other walls with a practically identical microhardness. The tube reveals a higher microhardness among all of the WAAM parts.

In-situ monitoring of mechanical testing enhances the quantitative properties of materials by revealing the deformation behavior with respect to time. In this work, the deformation of the tension samples was monitored by an optical microscope. Figure 13 presents the deformation of the vertical samples (build direction) from the test initiation to the fracture. The red marks show the gauge boundaries, and the white dotted line illustrates the fracture location in the sample. Elongation resulted in significant displacement of the red marks in Fig. 13B and C. The etched surface of the samples indicated that the walls were fractured at inner-layer regions; however, for the tube, the inter-layer zone was identified as the weak region.

The average ultimate strength (UTS), yield strength (YS_{0.2}), and elongation (%) are illustrated in Fig. 14. The strength properties of additive manufactured parts should be compared to the wrought (Ref. 14) and as-cast materials. To this end, four samples of the Inconel 718 plate, produced by the cold forming method, were examined as well. The tensile properties of as-cast material were provided by Bird et al (Ref. 15). It can be seen that the mechanical properties of the wrought material are higher than in the WAAM products, particularly the ductility which dropped by half. The
The average elongation was found to be maximum in wall I for which helium had been used as the shielding gas during the manufacturing process. The different values of mechanical properties in vertical and horizontal directions indicate anisotropic characteristics of the WAAM components. Wall IV has the lowest UTS among the WAAM products in both build and layer directions. The WAAM material exhibits lower strength properties by transitioning from build direction to the layer direction. Furthermore, the standard deviation of the tensile properties with five tensile specimens was calculated and illustrated in Fig. 14. The standard deviation was lower for UTS than YS and elongation in most of the WAAM products. Interestingly, the strength values for the WAAM components lie between the values for the cast and wrought alloys because of the fine columnar solidification structure in the WAAM material.

Discussion

Influence of Manufacturing Parameters on Physical Properties

This work examines the influence of some typical WAAM processing parameters, such as shielding gas, IIT, and deposition strategy on the prototypes’ characteristics. The measured dimensions of the walls are illustrated in Fig. 15. Based on the achieved geometries, using helium as the shielding gas led to a thin part with an increase in height. It should be mentioned that helium gas causes an arc contraction and distorted distribution of the arc current density (Ref. 16). Consequently, the weld bead is less wide and, higher, than when argon was used as the shielding gas (Ref. 17).

Different IIT influenced the ultimate geometry, indicating a shorter interlayer idle time, resulting in an inferior height in wall III. This short IIT prevents the deposited layer from cooling down; hence, the interlayer temperature increases impacting the built geometry (Ref. 18). It is worth mentioning that the deposition of a subsequent layer on the previous layer with an elevated temperature makes a wider melt pool and, as a result, a wide part was fabricated.

The deposition strategy was another parameter explored in this study. The height of wall IV on the left side (the start point of each layer) is more elevated than the other walls manufactured by a bidirectional deposition strategy. This bumpy shape resulted from a short pause to initiate the arc, and deposition occurred without moving the welding gun for a second. In the bidirectional deposition strategy, the start point of each layer was covered by the subsequent deposition layer and this bumpy edge is not observed in other walls. Moreover, the WAAM parts’ width and height were not varied by the alteration of the path strategy.

Microstructural Evolution and Mechanical Properties

The mechanical properties of the WAAM parts are dependent on the grain structure formed during the solidification. The solidification morphology is controlled by the temperature gradient (G) and solidification rate (R) during the process. In the WAAM parts made of Inconel 718, the austenitic grains are formed in the shape of columnar dendrites along with the heat flow or build direction. It should be noted that the dendrite columnar initiates with a small morphology in the interlayer region and progresses to the inner-layer area, developing to a larger size during the solidification as indicated in Fig. 7. By depositing the subsequent layer, epitaxial growth occurs and a fibrous texture is formed in the WAAM part.

Inconel 718 is a precipitation-strengthened Ni-base alloy. In the WAAM process, the Nb and C segregation occurs during the solidification. As a result, intermetallic eutectic and precipitates are formed in the inter-dendritic regions. The strengthening precipitates include $\gamma'$ ($\text{Ni}_3(\text{Al}, \text{Ti})$), $\gamma''$($\text{Ni}_3\text{Nb}$), and carbides. The intermetallics are identified as laves phase ($\Lambda_2\Phi$) and $\delta$ phase ($\text{Ni}_3\text{Nb}$) (Ref. 19). The phase transition from primary liquid ($L$) to $\gamma + \text{NbC}$ and $\gamma$ laves phase occurs at the temperatures of 1250° and 1200°C, respectively. As mentioned on the section of microstructural evaluation, the EDS analysis reported that laves, $\gamma'$, and NbC exist in the $\gamma$ matrix of WAAM parts. During solidification, the concentration of Nb and C enhances in the Liquid ($L$) while the dendrites grow. The higher Nb and C content leads to a densely distributed intermetallics formed in the inter-dendrite region (liquid phase).

The comparison of microstructures in the walls showed an insignificant difference in the solidification morphology.
and the volume fraction of intermetallics in the matrix. But both microstructural characters are comparable between the walls and the tube. The fine dendrites are beneficial for suppressing the formation of the coarse laves phase in the walls. However, a higher volume fraction of the intermetallics formed in the tube. In the tube’s inner-layer, the higher distribution and density of the intermetallics are attributed to reheating to almost solidus temperature when depositing the subsequent layer. Consequently, the precipitates coarsen at the elevated temperature in this region. The distribution of intermetallics is scattered with a lower density in the inter-layer region because the remelted region drives the diffusion of solutes toward the inner-layer zone, resulting in the formation of intermetallics in the interdendrites.

The microstructure of the WAAM products can contribute to their mechanical performance. As shown in Fig. 12, the tube and wall III have higher microhardness values compared to other walls, resulting from the higher interlayer temperature due to the lack of IIT (interlayer idle time) in those structures. It provides a higher chance of Nb-rich intermetallics precipitation, resulting in higher hardness (Ref. 20). The microstructure of the WAAM components (Fig. 8) confirms this conclusion.

The WAAM products exhibit an anisotropic mechanical performance in the layer and build directions. It should be noted that the tensile properties are direction dependent; however, the UTS has a larger standard deviation for the majority of the WAAM products in the horizontal direction, meaning there was a variation in the UTS of horizontal samples of the WAAM product. One reason could be that the horizontal (layer direction) samples are very location dependent on the walls due to slight variations in their microstructure caused by different thermal cycling and corresponding cooling rate.

Overall, the introduced parameters slightly impact the mechanical properties of the 718 WAAM materials. Interestingly, the average results of the WAAM material properties in this study were comparable to the findings by Xu et al. (Ref. 5). Among the mentioned processing parameters, helium shielding gas improved the elongation for the WAAM part. The thermal properties of helium gas produce a higher temperature gradient in the WAAM product during the deposition increasing the ductility.

The laves phase is considered to associate with loss of strength for WAAM Inconel 718. Figure 16 reveals the etched surfaces of horizontal and vertical tension samples after the test. In Inconel 718, the slip plane is {1 1 1}. The slip planes are formed along 45 deg, where the maximum shear stress occurs. It is evident that crack is initiated from the existing fine intermetallics and propagates along the slip planes. The separation of the laves phase from the matrix is observed in Fig. 16B. The slip lines do not pass through the large laves phases reducing the plastic deformation of the matrix (Ref. 21). As shown in Fig. 16, larger laves phases-formed in inter-dendrite regions are not at the slip line site exhibiting an elongation reduction in the WAAM products. It is worth mentioning that the tube exhibited the lowest ductility among the WAAM components because of the existence of large laves phases in the microstructure (see Fig. 9).

As previously mentioned, the tension samples of the tube fractured from the inter-layer region. It should be noted that the Nb microsegregation led to lower Nb concentration...
in this region, and the large laves phase would even conduct a lower Nb content in the matrix of the inter-layer zone. Those two factors could result in the formation of smaller volume fraction of strengtheners ($\gamma'$, $\gamma''$), leading to the weakness of the inter-layer region in the tube. Unlike the tube, finer laves phases were formed in the inter-layer region of the walls. Those fine laves phases are not simple to break up in that region (Ref. 21). Consequently, the walls fractured at their inner-layer zones due to the higher concentration of large granular laves phases.

### Fracture Morphology

Figure 17 illustrates the fracture surfaces of two WAAM components and the wrought material under SEM. The fracture surfaces of the wall structure were investigated in vertical (build direction) and horizontal (layer direction) orientations. The vertical samples of the WAAM products (tube and wall) exhibit an inter-granular failure. The vertical direction is the same as the columnar dendrites’ orientation. The microcracks were detected at the inter-dendrite region in vertical samples.
shown by arrows. Figure 18 shows region A specified in Fig. 17A. Interestingly, the chemical composition measurements (shown in Table 6) indicated the laves phase at inter-dendrite region (L) as the crack initiation site. The transition of the orientation displays a very distorted surface shown in Fig. 17E. In this orientation, the grain direction is perpendicular to the loading direction and is evident in Fig. 17F. The cracks were observed in the inter-dendrite region where the laves phase density is high. As a result, the WAAM material has a lower strength in the layer direction. The microvoids and tear dimples were observed at the fracture surface of the wrought material, as shown in Fig. 17H, indicating finer dimples leading to a higher ductility.

As discussed in the section on microstructure evaluation, the nitrides and oxides were dispersed in the WAAM microstructure. These inclusions were detected in the fractog-

<table>
<thead>
<tr>
<th>Point</th>
<th>Phase/Intermetallic</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>Cr</th>
<th>Fe</th>
<th>Ni</th>
<th>Nb</th>
<th>Mo</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Laves</td>
<td>0.20</td>
<td>1.46</td>
<td>1.75</td>
<td>13.80</td>
<td>15.35</td>
<td>44.11</td>
<td>19.98</td>
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</tr>
<tr>
<td>2</td>
<td>Laves</td>
<td>0.44</td>
<td>1.24</td>
<td>1.13</td>
<td>13.84</td>
<td>15.39</td>
<td>39.45</td>
<td>23.09</td>
<td>5.43</td>
</tr>
<tr>
<td>3</td>
<td>L</td>
<td>0.52</td>
<td>0.25</td>
<td>1.09</td>
<td>18.73</td>
<td>20.30</td>
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<td>2.50</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
<td>0.88</td>
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<td>1.12</td>
<td>17.95</td>
<td>19.47</td>
<td>52.29</td>
<td>5.08</td>
<td>2.66</td>
</tr>
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</table>
raphy. Based on the observations, most cracks were initiated from the laves phase particles and the detrimental impacts of these compounds were negligible. Figure 19 presents a TiN particle located in a dimple at the fracture surface of the tube sample.

Laves phase exists in the Inconel 718 parts produced by AM methods; however, the volume fraction of the laves phase in the WAAM parts is higher than the component manufactured by the powder bed fusion (PBF) method. In the direct energy deposition (DED), techniques such as the WAAM process, the cooling rate is significantly low resulting in severe Nb segregation and coarser columnar dendrites. The high cooling rate in the PBF method led to the finer solidification structure and higher strength, but a lower ductility as shown by Xu et al. (Ref. 5). Heat treatment is a key solution to improve the material’s strength, but it compromises the ductility. According to the Aerospace Material Specification (AMS) standard, heat treatment including solution and aging is used to dissolve most of the detrimental intermetallics and promote strengthening precipitates; nevertheless, it does not affect the solidification morphology. Homogenization could be performed prior to the solution step to impact grain sizes, resulting in creating an almost isotropic material; however, the homogenization also precipitated δ phase. The modified heat treatment method found by Seow et al. (Ref. 8) improves both ductility and tensile strength, but the achieved strength value is still lower than the tensile property of the as-deposited part using the PBF method (Ref. 22).

Conclusion

This research studied the processing parameters and geometry impacts on physical characterizations, microstructure, and mechanical properties of Inconel 718 WAAM parts. A tube and walls were produced with different sets of parameters using the GMAW method. The following conclusions were drawn as follows:

1. Helium (He) shielding gas narrows the arc current density. The narrow heat distribution produced a taller wall with thinner layers. The elevated heat concentration led to a bit finer solidification structure. However, the layers built using argon shielding gas are wider, resulting in a reduction in the part’s height. The overall tensile properties were equal using either of these shielding gases; however, the ductility was raised when using helium due to a higher cooling rate.

2. The variation of IIT did not impact the microstructure and mechanical properties significantly; nonetheless, the layer width increased by a reduction in the IIT.

3. The path strategy did not affect the layers’ dimensions in the WAAM process. The WAAM is a high-power deposition process that causes the grains to grow vertically and independently of the deposition direction.

4. The tube reveals coarser dendrites and intermetallics due to a different heat distribution during the manufacturing process. The larger Nb-rich intermetallics resulted in a higher microhardness among the WAAM parts. The tube’s tensile strength was in the range of the walls’ strength.

5. Inner-layer and inter-layer regions were identified in the WAAM products’ microstructure. The coarsening of precipitates occurred at the elevated temperature in the interlayer region. The higher distribution and density of the intermetallics result from reheating to almost solidus temperature due to the deposition of the next layer. The intermetallics were scattered with a lower density in the interlayer region due to the diffusion of solutes toward the inner-layer zone.

6. The mechanical properties of the WAAM products were found to be lower than the wrought material particularly the ductility. The WAAM products were weaker in the layer direction due to a higher layer phase density at the inter-dendrite region.

References


