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Microstructural characterisation of thick-walled wire arc additively manufactured stainless steel

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ABSTRACT

Wire arc additive manufacturing (WAAM) is a class of technologies suitable for producing large parts due to its high material deposition and building rates. Among the many possible materials processed by WAAM, austenitic stainless steels, e.g. 316L, are commonly employed. The structure of WAAM 316L thick parts has been studied extensively before. However, multiwalled or thick WAAM 316L parts remain largely unexplored. Hence, in this study, the microstructure of a thick 316LSi WAAM part is characterised in detail. The microstructure of the part consists of large and highly-oriented columnar grains dominated by epitaxial and competitive growth. The overlapping regions between neighbouring fusion zones contain long grains with a dominant <100> texture, which cross several layers and are aligned with the building direction. The grains’ internal microstructure consists of an austenite matrix, ferrite with locally varying dendritic morphologies and dispersed oxide inclusions. The texture spatially varies across the part, and this variation is correlated to the local thermal gradient induced by the building strategy and processing conditions used during the manufacturing of the thick-walled part.

1. Introduction

According to ISO/ASTM 52900 (2015), additive manufacturing (AM) is a general term used to describe the process of building a part by repeatedly adding material following a computer-aided design model. The additive nature enables realising intricate designs, fabricating near net shape parts, and reducing material wastage. Therefore, AM parts are found in many industries, such as aerospace, marine, and medical, as reported by Milewski (2017). Many AM technologies were developed to manufacture metallic parts with different resolutions and materials. The most suitable technique depends on a combination of factors, such as part dimension, production time, and desired resolution, as described in ASTM F3187 (2016).

Among many AM technologies, Wire Arc Additive Manufacturing (WAAM) is suitable for manufacturing large parts due to its high material deposition and building rates, as presented in the review focusing on wire-feed AM by Ding et al. (2015) and the general introduction of WAAM by Williams et al. (2016). WAAM uses an electric arc to continuously melt metallic wire feedstock to produce or repair large parts. Amid WAAM techniques, Gas Metal Arc Welding (GMAW) and Gas Tangsten Arc Welding (GTAW) are the most commonly used. The former is preferred as the wire acts as a consumable electrode, simplifying the required equipment and manufacturing process. Wu et al. (2018) reviewed the application of WAAM for different metals, such as titanium, nickel superalloys, aluminium, and steels. Thus, making it a suitable technology for many industries. For example, Ya and Hamilton (2018) investigated the manufacturing of a ship propeller for the marine industry. The authors explored different processing conditions and designs of the propeller, which RAMLAB later used for manufacturing the WAAPeller, a ship propeller with a diameter of 1.35 m. Greer et al. (2019) introduced new design rules for large parts and demonstrated them by manufacturing an excavator’s arm. Michel et al. (2019) presented the Modular Path Planning solution, which optimised the tool path prediction for complex parts. They demonstrated their tool by manufacturing an Airbus A320 aft pylon bracket mount. Another notable example is the stainless steel bridge by MX3D, which was tested...
focused on the precipitation of the precipitates in austenitic stainless steel. Differently, Hsieh and Wu (2012) phases in detail. Sourmail (2001) reviewed the most common pretance of welded stainless steels. Sourmail (2001) and Hsieh and Wu fabricated by casting, welding, or AM because of the processes structure) and Its microstructure consists of fast cooling. During these processes, the metal solidifies primarily as δ-ferrite, then as γ-austenite. Lippold and Savage (1982) studied the solidification and propensity of hot cracking of austenitic stainless steels weldments. The authors reported that the presence of δ-ferrite prevented hot cracking and reduced segregation in the material during processing. However, carbides and intermetallic phases preferentially precipitate at δ-ferrite and phase interfaces, locally deteriorating the corrosion resistance of welded stainless steels. Sourmail (2001) and Hsieh and Wu (2012) discussed the precipitation mechanisms of these secondary phases in detail. Sourmail (2001) reviewed the most common precipitates in austenitic stainless steel. Differently, Hsieh and Wu (2012) focused on the precipitation of the σ-sigma intermetallic phase, which deteriorates the properties of the stainless steel.

The structure of 316L fabricated using WAAM consists of coarse columnar grain structures oriented along the direction of maximum heat extraction, aligned with the building direction. The microstructure consists of γ-austenite matrix and dendritic δ-ferrite, with vermicular (skeletal-like shape) and lathy (lath-like shape) morphologies of the latter. The formation of these morphologies has been studied in detail for austenitic stainless steel weldments by Inoue et al. (2000). They reported that lathy ferrite is formed when a crystallographic orientation relationship is established between ferrite and austenite during solidification. Vermicular ferrite is formed when no crystal orientation relationship is present. Many authors have reported these microstructural characteristics for thin-walled parts for different WAAM processing conditions. For example, Cunningham et al. (2019) investigated the effect of heat input and interlayer cooling in the microstructure and mechanical properties of thin-walled 316LSi parts. They reported periodically varying grain structure, from fine to coarse grains, and microstructure with γ-austenite matrix and dendritic δ-ferrite with lathy and vermicular morphologies of the latter. Wang et al. (2019) explored the effect of different arc modes in the microstructure and mechanical properties of the 316L thin walls manufactured by WAAM. The authors identified large columnar grains with <100> texture and increased the secondary dendrite arm spacing (SDAS) along the building direction. These microstructural gradients were attributed to decreasing cooling rates as the layers are stacked due to the heating of previously deposited material.

The geometry of the part also affects the thermal conditions during the fabrication procedure. In thin-walled parts, the heat extraction is dominated by conduction between the deposited material and the base plate. In thick-walled parts, with multiple overlapping weld beads in width, heat is also extracted by the material from the sides, next to the dissipation to the baseplate. Thus, the thermal history in thick-walled parts is more complex than in thin-walled ones. Additionally, these thick parts are more challenging to build because of bead overlapping. Li et al. (2016) proposed and experimentally demonstrated a layers-overlapping strategy based on a revised layers-overlapping model to fabricate near-net-shape WAAM parts. The increase in manufacturing complexity of thick-walled parts means that, for different materials, a comparatively limited number of studies have focused on the metallurgy of thick parts produced by WAAM. Chen et al. (2017) studied the microstructure and mechanical properties of 316L, manufactured by WAAM (GMAW-based). They reported grain structure aligned with the building direction, and microstructure consisting of γ-austenite, δ-ferrite with vermicular and lathy morphologies and σ-sigma intermetallic phases. The precipitation of the intermetallic happened mainly in the interface between γ-austenite and δ-ferrite and was attributed to subsequent thermal cycles reaching the σ-sigma precipitation temperature. Wang et al. (2020), who also studied thick-walled 316L parts, identified periodically alternating structures, which they named overlapping and remelting areas. They reported that the overlapping area consists of large columnar grains with dominant <100> texture aligned with the building direction, whereas in the remelting area, the grains tend to be perpendicular to the fusion boundary.

Although studies report the microstructural characteristics of thick 316L parts, these are limited and do not provide an in-depth understanding of the spatial variations of different microstructural features across the thick part and their correlation to the WAAM procedure. Therefore, this research aims to provide a detailed understanding of the microstructural characteristics of WAAM 316LSi thick parts because of their high relevance for producing large-scale critical structural parts for, e.g., marine industries. For this purpose, the structure of a thick-walled part is experimentally investigated at different scales using various correlative microscopy techniques to identify and understand spatial variations in WAAM parts’ microstructure. Furthermore, a detailed understanding of the microstructure is essential in exploiting the versatility that WAAM offers. For example, locally tailoring the structure and the mechanical properties may significantly extend WAAM parts’ applicability with specific requirements and applications.

2. Materials and methods

2.1. Material fabrication

The fabrication of the thick-walled part was performed using a Panasonic TM 2000 welding robot equipped with a Panasonic YT – CET351 Active torch. The part consisted of a block of approximately 150 mm x 40 mm x 25 mm built on a 200 mm x 100 mm x 10 mm hot-rolled 316L base plate using a bidirectional scanning path as schematically shown in Fig. 1. Each layer consisted of 10 straight and parallel weld beads stacked along the transverse direction with the same deposition direction. Subsequent layers were deposited with a similar stacking of the weld beads but with opposite deposition directions. The feedstock was 1 mm diameter LNM 316LSi (AWS A5.9 grade) wire from Lincoln Electric with a composition presented in Table 1. This wire has higher silicon content than 316L to increase the fluidity of the molten material, thus increasing weldability. The WAAM procedure was performed on a water-cooled copper welding table under the conditions, based on RAMLAB’s expertise for processing 316LSi, summarised in Table 2. A partial layer consisting of 5 weld beads was deposited on top of the manufactured part, as shown in Fig. 2a and d.

2.2. Microstructure characterisation

Metallographic specimens in the XZ (transverse–building cross-section), YZ (deposition–building cross-section) and XY (transverse–deposition cross-section) planes are extracted from the middle of the part using wire electro-discharge machining. These specimens are prepared for analysis using standard metallographic procedures, which consisted of mechanical grinding with SiC from 200 to 1200 grit number followed by mechanical polishing with 3 μm diamond suspension and 0.05 μm colloidal silica. Two different chemical reagents, based on the principles of colour metallography presented by Voort (2004), are used to reveal the structure of the material:

1 The grain structure is revealed using a solution consisting of 300 mL H2O, 60 mL HCl and 3 g K2Cr2O7, in which the specimens were immersed in the solution for 60 s to provide enough contrast between different grains;
Typical composition (wt%) of the LNM316LSi wire (AWS, 2017).

Table 1

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01</td>
<td>1.8</td>
<td>0.8</td>
<td>18.5</td>
<td>12.2</td>
<td>2.5</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2

WAAM (GMAW-based) processing conditions used for manufacturing the thick-walled part.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>20.5 V</td>
</tr>
<tr>
<td>Current</td>
<td>160 A</td>
</tr>
<tr>
<td>Wire-feed speed</td>
<td>8.5 m/min</td>
</tr>
<tr>
<td>Scanning speed</td>
<td>0.75 m/min</td>
</tr>
<tr>
<td>Contact tip distance</td>
<td>15 mm</td>
</tr>
<tr>
<td>Interlayer temperature</td>
<td>150 °C</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>Ar + 1% CO₂ + 18% He</td>
</tr>
<tr>
<td>Shielding gas flow</td>
<td>20 L/min</td>
</tr>
<tr>
<td>Parallel/ bead spacing</td>
<td>3.85 mm</td>
</tr>
<tr>
<td>Height/ layer spacing</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>Weld beads per layer</td>
<td>10</td>
</tr>
<tr>
<td>Number of layers</td>
<td>10</td>
</tr>
</tbody>
</table>

The different phases are revealed using an electrolytic etching procedure, consisting of a 50 g NaOH and 300 mL H₂O solution with 2 V direct current for 10 s.

The exposed microstructure of the specimen is analysed using optical and scanning electron microscopy (SEM). An overview of the entire specimen cross-section is obtained by taking a series of micrographs with a (Sensofar S Neox) optical microscope (OM) in bright-field imaging mode. Subsequently, these micrographs are stitched using the Microscopy Image Stitching Tool (MIST) plugin for Fiji, developed by Bachmann et al. (2010).

### 3. Results

#### 3.1. Grain structure

The WAAM part and overview of the grain structures of different cross-sections are presented in Fig. 2. Here, the X-axis, Y-axis and Z-axis are parallel to the transverse, deposition and building directions, respectively. The YZ (Fig. 2b) and XZ (Fig. 2d) cross-sections reveal a structure dominated by large and elongated columnar grains, most clearly seen in the XZ-plane. The grains are aligned with the building direction in the centre of the part but are directed towards the sides near the edges of the part. Besides the grain structure, the fusion lines can also be identified in the optical micrographs. In the YZ (Fig. 2b) and XY (Fig. 2c) cross-sections, the fusion lines exhibit a corrugated profile due to the material transfer during the manufacturing procedure. Additionally, a few round macro defects are present, suggesting gas porosity, but the overall part is bulky with a low amount of defects as expected for WAAM parts.

The grain growth direction across the XZ plane is shown in Fig. 3 and confirms the grain’s expected preferential alignment along the building direction. Furthermore, regions with prevalent grain alignment are noticeable with a periodic trend across the part, suggesting a strong influence of the tool path and processing conditions in the part’s microstructure.

A magnified micrograph of the XZ plane, where the fusion boundaries are visible, is presented in Fig. 4. In Fig. 4a, the fusion boundaries that define neighbouring fusion zones are highlighted. The distinct zones exhibit a bell-shaped penetration profile, the distance the fusion extends into the previously deposited material, resulting from the processing parameters employed to manufacture the sample. The grains tend to grow perpendicular to the fusion boundary, which is expected to correspond with the direction of maximum heat extraction. In Fig. 4b, the grain growth direction is studied from the local angular map, confirming the tendency of the grains to grow perpendicular to the fusion interface. Moreover, strong alignment is observed in the overlapping region between neighbouring fusion zones, confirming the observations in Fig. 3.
3.2. Fusion zone geometry

The fusion zone’s geometry depends on the combination of the material, the shielding gas, and processing conditions. Here, the fusion zones are traced from the XZ cross-section, and their geometry is studied using the mean fusion zone shape, obtained using the dedicated mapping methodology presented by Belotti et al. (2021). Fig. 5a shows the traced outlines of the fusion zones. The red outlines (36 fusion zones) were used to calculate the mean shape, and the yellow ones (28 fusion zones) were added to study the spatial variations in geometrical features (i.e. area, width, and height). The outermost weld beads (right and left edges of the part) and layers (first and tenth) were not considered because they do not represent the bulk of the thick-walled WAAM part. The aligned outlines, the calculated mean fusion zone shape and the definition of width and height are shown in Fig. 5b. As expected, the shape of the fusion zones varies across the WAAM part, as shown in Fig. 5c. However, the calculated mean fusion zone shape closely represents the average geometrical features of the experimental data. Interestingly, the average width and height of the fusion zones also closely correlate with the parallel bead spacing set value (3.85 mm) and vertical layer spacing (2.2 mm) of the welding robot during the manufacturing process. This correlation suggests that the employed definitions of width and height of the fusion zone are adequate to study spatial variations across the part. In Fig. 6, the difference between each fusion zone and the mean shape in terms of area, width, height and rotation are visualised over the XZ-plane. In the bulk of the thick-walled part, no significant trends can be identified. However, close to the left and right edges, smaller areas of the fusion zones are found (Fig. 6a). The reduction in area is concurrent to variations in the fusion zones’ width and height, as shown in Fig. 6b and c. These geometrical variations result from uneven
layer height, which increases the contact-tip working distance and the wire resistance, thus, reducing the current and the local heat input. Additionally, the leftmost and rightmost fusion zones are rotated compared to the mean one, as seen in Fig. 6d. The rotation is caused by the part’s geometrical differences closer to the boundaries during manufacturing due to the uneven layer height.

The periodically and spatially varying grain growth directions are shown in Figs. 3 and 4b. Next, the grain growth directions inside each fusion zone are mapped to the mean fusion zone shape (Fig. 5b). All this information is averaged using the mapping methodology following the procedure proposed by Belotti et al. (2021). The resulting average grain growth direction and the corresponding degree of uniformity mapped inside the mean fusion zone shape are presented in Fig. 7a and b. The average grain growth direction closely represents the grain growth direction inside the fusion zones, as noticeable from the high degree of uniformity in the data. These results confirm the periodic grain structure across the part and grains’ tendency to grow perpendicular to the fusion boundary.

3.3. Solidification structure

The solidification structure of the WAAM part contains γ-austenite and δ-ferrite, as empirically described by constitution diagrams such as Schaeffler (1949) and Delong (1974). The used steel, with its nominal composition shown in Table 1, primarily solidifies as δ-ferrite with a vermicular (skeletal-like) or lathy (lath-like) morphology depending mainly on its alignment with the heat flow direction and the crystallographic orientation relationship with austenite, as previously investigated by Inoue et al. (2000). However, the δ-ferrite morphology varies across the part and over a fusion zone, as shown in Fig. 8. In the bulk of the fusion zone, the δ-ferrite exhibits mainly vermicular and lathy morphologies. However, at the fusion interface, taken as the first identifiable transition region with microstructure variation between two neighbouring fusion zones, other morphologies are also present, such as columnar and globular structures. The variation in the δ-ferrite morphology has been studied in the welding community. Suutala et al. (1979) investigated the solidification and microstructure of austenitic stainless steel welds. The authors found that the δ-ferrite morphology depends on the composition of the weld metal. Variations in the material
composition result in different solidification modes, leading to different phase morphologies. David (1981) studied the variation of the δ-ferrite morphology in stainless steel multipass welds. The author reported variations in the shape of δ-ferrite due to subsequent thermal cycles in the multipass welding procedure. In summary, the δ-ferrite morphology is linked to the local material composition, cooling rate, formation mechanism, and crystallographic orientation relationship with austenite. Besides the morphology, the ferrite fraction also varies across a fusion zone, see Fig. 9. Although the phase fraction locally varies, there is no significant change in the average fraction (approximately 10.3 %) along the building direction.

Besides γ-austenite and δ-ferrite, dispersed round-shaped inclusions are present in the material, as shown in Fig. 10. The nature of these particles has been identified using EDX analysis, shown in Fig. 11. The elemental analysis reveals that these inclusions are rich in oxygen, silicon and manganese, suggesting that they are oxide impurities resulting from oxygen pick-up during the part’s manufacturing.

Fig. 6. Variation of the fusion zones’ area (a), width (b), height (c) and rotation (d) compared to the mean fusion zone shape. A higher variation is observed in the outermost fusion zones, close to the left and right edges, resulting from heat distribution profiles different from those in the middle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 7. (a) Average grain growth direction, obtained from all the individual grain growth directions shown in Fig. 3, mapped inside the mean fusion zone shape. (b) The corresponding degree of uniformity is defined as $2D - 1$, where $D$ is the largest eigenvalue of the local grain growth direction, as Belotti et al. (2021) proposed. A high degree of uniformity translates into a small variability in the local grain growth direction across all the traced fusion zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
3.4. Texture

Additively manufactured parts often result in highly oriented structures, as shown in Fig. 3. The preferred orientation is also visible in terms of crystal orientation or texture. Fig. 12 shows the γ-austenite crystal orientation map with the building (Fig. 12a) and deposition (Fig. 12b) direction, respectively. A preferred orientation with the $<100>$ directions along the building direction is present. This is expected, as $<100>$ is the easy-growth direction (EGD) for cubic crystal structures, as discussed in the solidification theory book by Rappaz and Dantzig (2009), and the EGD should be aligned with the direction of the maximum temperature gradient, which aligns with the building direction. This alignment is most pronounced in the overlapping region between neighbouring fusion zones. Consequently, large columnar grains are present in this area. The pole figures, shown in Fig. 12c, also confirm the strongly textured material with a dominant $<100>$ orientation in the building direction.

Although the bulk structure has a dominant $<100>$ texture along the building direction, it spatially varies across the transverse direction of the WAAM part. It was shown in Fig. 3 that the grains tend to grow.

![Fusion boundary](image1)

![Columnar ferrite](image2)

![Globular ferrite](image3)

![Vermicular ferrite](image4)

![Lathy ferrite](image5)

Fig. 8. Local solidification structure of the part consisting of an γ-austenitic matrix and dendritic δ-ferrite. In the centre of the fusion zone, mostly vermicular and lathy δ-ferrite are present, but columnar and globular morphologies emerge at the fusion boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

![Austenite](image6)

Fig. 9. Ferrite fraction on the 1st, 5th, and 9th layers of the WAAM part, showing no significant differences along the building direction. The boxplot is explained in the caption of Fig. 5c.

![Ferrite fraction](image7)

Fig. 10. Higher magnification micrograph taken in the centre of a fusion zone, revealing dispersed round-shaped inclusions.
perpendicular to the fusion interface and that close to the edges of the part, the grains are directed towards the edges of the sample due to a different heat extraction direction and fusion zone shapes. In terms of texture, this spatial variability is emphasised in Fig. 13. A periodically repeating texture with dominant $<100>$ directions aligned with the building direction is present in the overlapping region, followed by $<100>$ directions perpendicular to the fusion interface in the centre of the fusion zone. Towards the edges, a $30^\circ$ rotation of the $<100>$ texture with respect to the building direction can be noticed. This texture rotation is attributed to different fusion zone shapes at the side faces of the part, which are rotated compared to the ones in the centre (Fig. 6d), indicating that the direction of the temperature gradient has rotated accordingly. The rotation and change in the temperature gradient direction result from the uneven layer height, which translates into the edge weld beads being deposited on a curved surface.

A YZ (deposition-building direction) cross-section was analysed in

Fig. 11. Chemical characterisation maps obtained with EDX analysis showing the different chemical compositions of $\gamma$-austenite (Ni-rich) and $\delta$-ferrite (Cr-rich). Additionally, the maps also reveal that the inclusions are rich in oxygen, silicon, and manganese. The top left image shows the SEM secondary electron image with inclusions visible as dark spots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 12. Austenite crystal orientation maps of the XZ plane presented as inverse pole figure (IPF) maps showing the crystallographic direction corresponding to the building direction (a) and deposition direction (b); the colours represent the crystal orientations, as indicated by the colour scale on the right. (c) (100), (110) and (111) pole figures related to the austenite phase showing a strong texture aligned with the building direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
terms of texture, shown in Fig. 14. Similar to the XZ plane, a dominant orientation of <100> along the building direction is clearly visible in the IPF maps in Fig. 14a and b. The pole figures, Fig. 14c, confirm the strong texture along the building direction, and together with the vertically elongated grains, suggest that this particular analysed YZ cross-section passes through the overlapping region of fusion zones. This suggestion is enhanced when analysing another YZ cross-section in the centre of the fusion zones, shown in Fig. 15. The IPFs (Fig. 15a and b) show less elongated and textured grains parallel to the building direction. Compared to the cross-section presented in Fig. 14, the <100> texture is slightly rotated towards the X-axis (parallel to the transverse direction), as highlighted by the pole figures in Fig. 15c. These identified spatial differences result from various aspects, such as variations in the weld bead (parallel) and layer (vertical) stacking and the cross-section position relative to the fusion zone shape. The grains in the overlapping region are elongated along the building direction, and the cross-section presented in Fig. 14 clearly reveals this. The finer and less textured structure shown in Fig. 15 suggests that the grains were not sectioned along their longest axis, which is the case for the central region of the fusion zones. Besides the preference of <100> directions along the building direction, a weaker <100> texture along the deposition direction is identified in Figs. 14c and 15c. This preferred texture arises from the directional solidification of the molten material following the deposition direction.

4. Discussion

Thin-walled 316LSi WAAM parts have been analysed extensively. However, thick parts have received much less attention. The thermal history of block samples is complex since the material is repeatedly heated and cooled at high rates, and the heat extraction is multidirectional. This complex thermal history depends on the combination of processing conditions, such as tool path design, heat input, shielding gas, the geometry of the part, and material. The combination of all the aspects mentioned above affects the structure and, consequently, are also expected to affect the mechanical properties of thick WAAM parts.

It has been widely reported that many AM processes result in an oriented and relatively coarse microstructure compared to traditional manufacturing processes, as shown in the reviews by Collins et al. (2016) and DebRoy et al. (2018). As seen in Figs. 2d and 3, the structure is formed by large and oriented grains. Near the fusion boundary, the structure is dominated by epitaxial growth, which means that pre-existing grains act as substrate, and crystals with similar crystallographic orientations nucleate from the molten material, as discussed by Kou (2003), who compiled the key aspects of welding metallurgy for metallic materials for the different fusion welding processes. Epitaxial growth is clearly identified in optical micrographs (Fig. 4a) and crystal orientation maps (Fig. 12a and b). The coarse and elongated grains result from the preferred growth direction aligned with the temperature gradient, which tends to be perpendicular to the fusion boundary. Each crystal structure has an energetically favourable direction of growth, i.e. <100> for face-centred cubic and body-centred cubic structures, which, when aligned with the temperature gradient, promotes the growth of those grains. The described mechanism is known as competitive growth and dominates the grain structure away from the fusion boundary. These two solidification mechanisms dominate the structure of thin or thick-walled additively manufactured parts. Therefore, highly oriented and textured structures are mostly reported, which translates into an anisotropic mechanical behaviour, as shown experimentally for 316L steel thin walls by Cunningham et al. (2019), and Wang et al. (2019), and for thick walls by Chen et al. (2017) and Wang et al. (2020).
**Fig. 14.** IPFs with respect to the building direction (a) and deposition direction (b) for the YZ plane in the overlapping region. The colours represent the crystal orientations, as shown by the colour scale. (c) (100), (110) and (111) pole figures related to the austenite phase showing a strong texture aligned with the building direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

**Fig. 15.** IPFs with respect to the building direction (a) and deposition direction (b), and corresponding (100), (110) and (111) pole figures (c) for the YZ plane in the centre of the fusion zones. The colours represent the crystal orientations, as shown by the colour scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
Recently, this anisotropic mechanical behaviour, in terms of engineering yield stress, has also been numerically demonstrated using crystal plasticity finite element simulations by Van Nuland et al. (2021).

Similar metallurgical characteristics have also been reported for other austenitic stainless steels, such as 304L. Laghi et al. (2020) performed microstructural and mechanical characterisation of 304L thin walls manufactured by WAAM. They analysed three sets of specimens, one extracted along the building direction (vertical), one along the deposition direction (horizontal), and another extracted at 45° from the deposition direction (diagonal). Their results showed an oriented structure, and anisotropic elastic and plastic mechanical properties, with the diagonal and vertical specimens showing the highest and lowest properties in both regimes, respectively. Kyvelos et al. (2020) studied the same material and reported similar metallurgical features. They attributed the higher stiffness for the diagonal samples to a <110>-texture, whereas the vertical and horizontal samples exhibited a dominant <100>-texture. The anisotropy in the yield and ultimate tensile stresses were attributed to differences in the mean free path for dislocations to travel for specimens sampled in different directions. Laghi et al. (2021) recently extended their work on elastic anisotropy by introducing an experimentally validated orthotropic elastic model for the same material. They reported that the specimens extracted at different orientations had distinct preferred textures, with a vertical specimen with a preferred <100>-texture, a horizontal one exhibiting <100> and <110>-textures, and the diagonal specimen having preferred a <111>-texture. These textures were used to explain the anisotropy in the stiffness, where the specimen at 45° and the one aligned with the building direction showed the highest and lowest stiffness, respectively.

The manufacturing conditions, i.e. scanning strategy, power, travel speed and shielding gas, may lead to a different microstructure. For example, the shape of the fusion zones may be different (Fig. 6), and consequently, the solidification structure will follow (Figs. 2d and 13). Near the edges, the fusion zones are rotated (Fig. 6d), which results in grains growing towards the WAAM part’s sides (Fig. 3). Additionally, the periodic stacking of the weld beads (parallel) and layers (vertical) affects the part’s microstructure. Regions with coarse grains aligned with the building direction are periodically found at the overlapping regions between adjacent fusion zones (Fig. 7). These regions promote unhindered grain growth, resulting in grains that are several millimetres long (Fig. 2b and d) with a preferred <100>-texture along the building direction (Figs. 12 and 13). On the other hand, excessive grain growth is prevented in the fusion zone’s bulk. This spatially varying granular structure results from variations in the fusion boundary profile (Fig. 7a), affecting the competitive growth along the part. When the profile exhibits a negative curvature (centre of the fusion zone), excessive competitive growth is prevented because the grains tend to grow towards the same point. Differently, when the curvature is positive (overlapping regions), grains can grow effortlessly, as shown in Figs. 7 and 12. These distinct and periodic structural characteristics agree with what has been reported by Wang et al. (2020). The authors reported that these periodic structural characteristics translate into anisotropic mechanical properties at different loading directions. An anisotropic mechanical response is expected in both elastic and plastic regimes. The presence of the periodic structure may lead to a spatially dependent local stiffness related to the material’s local texture depending on the loading conditions. For instance, the overlapping region may exhibit a low local stiffness due to the dominant grains oriented with the building direction, whereas the centre of the fusion zone has a high stiffness because of the spatially varying texture following the penetration profile of the fusion zone. In terms of anisotropy in the plastic regime, the spatial dependence of the texture and macroscopic yield stress has been studied by Van Nuland et al. (2021). They reported that the spatial location of a preferred texture, i.e. as identified in the overlapping regions, prominently influences the macroscopic yield stress. The material may exhibit unstable plastic behaviour due to spatially dependent strain localisation when loaded in specific directions because of the periodic structure, as also reported by Wang et al. (2020). Thus, the grain structure, i.e. refinement, should be tailored by modifying the manufacturing conditions to prevent excessive grain growth. Cunningham et al. (2018) reviewed different strategies to increase the quality of the WAAM parts in terms of phases, grain refinement, residual stresses, and thermal-based inhomogeneities. For example, employing different shielding gases and applying the weaving motion of the welding torch allows for changing the fusion zone’s penetration profile and, consequently, the grain structure. Also, altering the weld bead and layer stacking by changing the deposition strategy and the volumetric heat input may allow locally refining the grain structure. These are a few possibilities for tailoring the grain structure, which will be explored in future work.

The part’s microstructure comprises more than just the grain structure, as shown in Figs. 8 and 10. γ-austenite and δ-ferrite were the two major phases identified in the material, which agrees with expectations from the welding metallurgy of stainless steels presented by Lippold and Kotecki (2015). The microstructure results from the primary solidification structure (γ-austenite or δ-ferrite) and post-solidification phase transformations. The material’s chemical composition defines the primary solidification structure, and the phase transformations are affected by cooling rates and subsequent reheating steps. The morphology of the δ-ferrite depends on both the solidification and post-solidification transformations, with vermicular and lathy being the most common for austenitic stainless steels. However, as seen in Fig. 8, the δ-ferrite morphology locally varies across a fusion zone, from cellular and globular morphologies at the fusion interface, to vermicular and lath morphologies in the centre. These variations are a result of local cooling rates, chemical composition, subsequent thermal cycles, and the crystallographic orientation relationship between γ-austenite and δ-ferrite, as reported by Suutala et al. (1979), David (1981) and Inoue et al. (2000). These morphologies periodically repeat for unique fusion zones across the WAAM samples, in agreement with what has been reported for thin parts by Cunningham et al. (2019) and Wang et al. (2019), and thick parts by Chen et al. (2017) and Wang et al. (2020), for different processing conditions. The variations in the morphology are followed by local variations in the ferrite content, but the overall ferrite fraction (approximately 10.3%) is not significantly affected (Fig. 9).

As reported in Fig. 10, fine and dispersed oxide inclusions have also been identified besides γ-austenite and δ-ferrite. The inclusions are caused by the presence of oxygen in the melt pool during the additive manufacturing process. Oxygen may be picked up due to improper shielding during fabrication, i.e. welding torch moves away as the part is exposed to a mixture of air and shielding gas. In addition, employing shielding gases and wires with oxygen in their composition may promote the formation of oxides during the solidification of the molten material, as has been discussed for stainless steel weldments by Folkhard (1988). An oxide layer forms on top of the deposited material, which can be mixed with the melt pool during the deposition of the subsequent material layer if the oxide layer is not properly removed. Although promoting the formation of oxide inclusions, shielding gases with small additions of carbon dioxide, like the one used in this work, are used to stabilise the manufacturing process, increase the welding speed, and improve the weld bead geometry, as reported for GMAW by Mvola and Kah (2017) and Kou (2003). The elemental characterisation (Fig. 11) reveals that the inclusions are, besides oxygen, rich in silicon and manganese. These two elements are known to be strong deoxidisers and are commonly used for reducing the amount of oxygen in the melt pool, as discussed in the welding metallurgy book by Folkhard (1988). These oxide inclusions are very brittle and could act as crack initiation sites when mechanically loaded, as reported by Wang et al. (2020, 2019).

The grain structure is dominated by epitaxial and competitive growth in both thin and thick WAAM parts, resulting in coarse columnar grains with strong texture. In addition, similar phases have been reported, showing periodic repeatability in terms of morphology and
phase fraction. However, thick parts have a more complex microstructure by having periodic patterns related to the fusion zone shapes, grain structure, and texture. This periodic repeatability results in parts with spatial variations in their microstructural features linked to their processing conditions and tool-path strategy.

5. Conclusions

In this study, the microstructure of a stainless steel 316LSi thick wall additively manufactured part using Wire Arc AM (GMAW-based) was discussed. The conclusions from the study are summarised as:

1. The WAAM part exhibits a periodic fusion zone and granular structure. In the overlapping region between neighbouring fusion zones, coarse and highly oriented grains and a dominant <100> texture along the building direction are present due to uncontrolled competitive growth. In the centre of the fusion zone, the grain structure is more refined, and the <100> crystal direction is mainly perpendicular to the fusion boundary.

2. The microstructure consists of austenite, ferrite, and fine oxide inclusions. The ferrite morphology locally varies across a single fusion zone, exhibiting mostly cellular and globular morphologies at the fusion interface and vermicular and lathly in the centre. This spatial variation translates into changes in the local fraction of ferrite. Similar variations are identified in different fusion zones, with periodic repeatability of the morphology and small ferrite fraction variations along the building direction.

3. Remarkable spatial variations in the part’s structure are present due to the additive manufacturing procedure. These variations are identified in terms of fusion zone shape, granular texture, and phases present.

By controlling the characteristics of the periodic microstructure and spatial variability through the AM processing conditions and the building strategy, the built part’s orientation-dependent mechanical properties can be controlled in the future.

CRediT authorship contribution statement

L. Palmeira Belotti: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft. J.A.W. van Dommenelo: Conceptualization, Funding acquisition, Methodology, Resources, Project administration, Supervision, Writing - review & editing. M.G.D. Geers: Conceptualization, Funding acquisition, Methodology, Resources, Project administration, Supervision, Writing - review & editing. C. Goulas: Investigation, Methodology, Writing - review & editing. W. Ya: Investigation, Methodology, Resources, Writing - review & editing. J.P.M. Hoefnagels: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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