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Static Properties and Fatigue Strength of Wire Arc Additive Manufactured 316L

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***Abstract*—The use of direct energy deposition (DED) has become much more common recently and in the future the DED technology will be used even more widely. Wire arc additive manufacturing (WAAM) technology has become much more widespread because it can be done cost-effectively with normal cold metal transfer (CMT) welding equipment. There is still a lack of information on the fatigue strength of parts made with different welding wires. This paper focuses on the mechanical properties of AISI 316L WAAM printed parts as well as bending fatigue strength. The average microhardness values were measured along the build direction. The optical microscope and EBSD detector were used to investigate the microstructure. The tensile strength and bending fatigue strength of the WAAM printed 316L were evaluated. The EBSD investigation revealed that due to high heat input of the WAAM process, the remelting of each consecutive deposited layer caused epitaxial grain growth in the structure, leading to coarse columnar grain structure. There were no visible pores in the microstructure of the WAAM 316L. The hardness of the WAAM 316L was homogenous in the build direction. Based on tensile strength tests, the strength in the deposition direction was greater than in the build direction which is explained by the anisotropy generated in the deposition. The results revealed that the fatigue limit of the WAAM 316L is comparable to that of 316L sheet metal. The fatigue strength of the WAAM 316L was significantly higher in the high cycle fatigue regime compared to the fatigue strength of the powder bed fusion (PBF-LB) printed 316L.**

Keywords—wire arc additive manufacturing, stainless steel, fatigue strength, tensile strength

I. Introduction

The industry has realized that manufacturing especially large pieces with powder bed fusion (PBF) technology is not possible or not cost-efficient and therefore the adoption of direct energy deposition (DED) methods including wire arc additive manufacturing (WAAM) has increased. Parts produced with WAAM technology can e.g., replace parts made by casting. This is significant in the sense that the production of cast parts is usually mass production, but with WAAM technology production of small series of parts is possible. Utilizing DED methods also has advantages compared to traditional manufacturing methods, such as freedom of design of parts, material saving and, automated production [1].

Implementation of the WAAM method is possible, for example, for companies that do robotic gas metal arc welding (GMAW). Especially if the company has cold metal transfer (CMT) welding equipment in production use, the implementation of the WAAM method is relatively easy. The advantage of CMT equipment is lower heat input to the part. The WAAM method can improve the company's productivity because WAAM parts can be manufactured when the welding production capacity is not in full use.

WAAM technology has seen rapid development in the past few years and novel solutions have been introduced for both industry and research use. In particular, there has been a development in welding equipment, which is specially designed for WAAM use. The software development of WAAM devices has also been significant. Properly designed WAAM parts are topologically optimized so that the strength of the product is at a sufficient level, but there is no need to use extra material.

In the WAAM process, the parts are built one welded layer at a time but since there are a considerable number of layers on top of each other, the microstructure of the part may be different from the individual weld seam because of the heat accumulation [2-5]. In the WAAM process, a considerable amount of heat is transferred to the part, so usually, idle time must be used, especially in the production of small parts [6-7]. The idle time also aims to improve the homogeneity of the piece in the build direction, because excessive heat input at the start and end of the deposed layer is often a problem in parts manufactured with the WAAM method [8].

Due to intermittent heat input, the microstructure of WAAM printed parts has been studied in several publications. Sasikumar et al. [9] investigated WAAM of stainless steel 316L and Inconel 625. Their observation was that microstructure of 316L was mainly composed of columnar and equiaxed dendrites.

For companies to be able to utilize the parts and structures produced by WAAM, they must have extensive information about the material properties of the parts. It is especially important to know the fatigue resistance of the parts because fatigue resistance is one of the most important factors that must be taken into account in the design of steel products.

Several publications have been made on the utilization of the WAAM method and the properties of WAAM parts, but the fatigue strength of the parts in particular has not been sufficiently studied yet. This paper investigates the bending fatigue strength of WAAM printed 316L. The paper also investigates the microstructure, hardness, surface roughness and tensile strength of the WAAM printed 316L.

II. EXPERIMENTAL METHODS

A. WAAM equipment and welding wire

A Fronius TransPuls Synergic 2700 CMT welding machine was used in the WAAM experiments. In the settings of the welding machine, the thickness of the material was set to 1.5 mm, which allowed the device to automatically adjust the wire feed, current, and voltage. Welding program no. 12 CrNi 19 9 ER 308 was selected on the machine. The deposition speed was 0.64 m/min and the lift between each layer was 1.3 mm. The idle time between each deposited layer was 90 s. 92% Argon + 8% CO_2 gas was used as a welding gas.

1.2 mm thick INEFIL INOX AISI 316LSI stainless steel wire was used as welding wire. The mechanical properties reported by the welding wire manufacturer are shown in Table 1. The chemical composition of the welding wire can be seen in Table 2.

TABLE I. MECHANICAL PROPERTIES OF THE 316L WELDING WIRE

Material	**Yield strength**	**Tensile strength**	**Elongation**
	[MPa]	*[MPa]*	*[%]*
316LSI	440	560	40

TABLE II. CHEMICAL COMPOSITION OF THE WELDING WIRE

C	**Si**	**Mn**	**Ni**	**Cr**	**Mo**
0.02	0.80	1.70	12.20	18.50	2.50

B. Experimental setup

The deposition track was oval-shaped, and every other layer was started from the opposite side of the track and at the same time, the deposition direction was changed to the opposite. Starting points of the deposition have been presented in Fig 1. The length of the straight part of the track was 140 mm, the width of the part was 20 mm, and the curved part radius was 10 mm. The WAAM printed part can be seen in Fig. 1. There was a 20 mm thick substrate used on which the WAAM part was deposited.

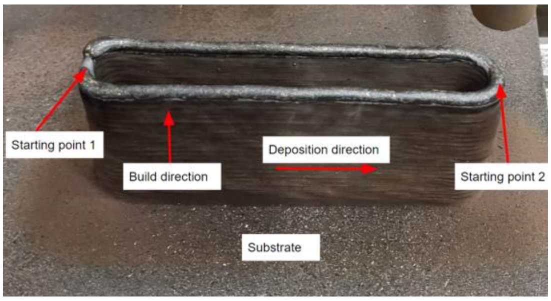


Fig. 1. Diagram of the WAAM printed part. The printing directions and starting points for printing are shown in the figure.

C. Mechanical characterization

Tensile and fatigue test specimens were manufactured from the WAAM part by machining approximately 1 mm on both sides of the WAAM part so that the uneven surface layer could be removed. The result of the machining was a 2 mm thick plate, from which tensile and fatigue test specimens were laser cut and machined to the right dimensions.

Tensile tests were made using an Instron 8802 universal testing machine according to the standard SFS-EN ISO 68921:2016. A constant loading rate of 1.0 mm/min was used in tensile test experiments. Hardness measurements were made with Innovatest Falcon 500 Vickers hardness testing machine and 0.2 kg load. Hardness measurements were made every 0.1 mm distance. Surface roughness measurements were made with a Keyence VHX-200 optical microscope and measurements were made in the build direction.

The fatigue strength of the specimens was determined using an in-house manufactured reversed flexural bending machine based on a WEBI machine originally manufactured by Carl Schenck. A stress ratio of R = -1 was used in the bending fatigue tests. The tress ratio is defined as a ratio of minimum stress to maximum stress in one cycle of loading in a fatigue test. Stress amplitudes from 120 MPa to 520 MPa were used. Each specimen was calibrated separately with a force sensor.

SLM 280 HL machine was utilized to the manufacturing the PBF-LB samples. PBF-LB samples were manufactured with power of a 200 W, speed was 800 mm/s, the layer thickness of 30 µm, hatch spacing of 120 µm and laser spot diameter was 0.1 mm.

Samples for microstructure examinations were polished and etched with 68% of nitric acid. Optical microscopy (Keyence VHX-200) was utilized to determine the microstructure. JEOL JSM-7900F electron microscope and Oxford Instruments Symmetry EBSD detector were utilized in the EBSD evaluation. The voltage used was 20 kV and the working distance was 17 mm. For EDS, the voltage was 10 kV and WD 8 mm.

III. RESULTS AND DISCUSSION

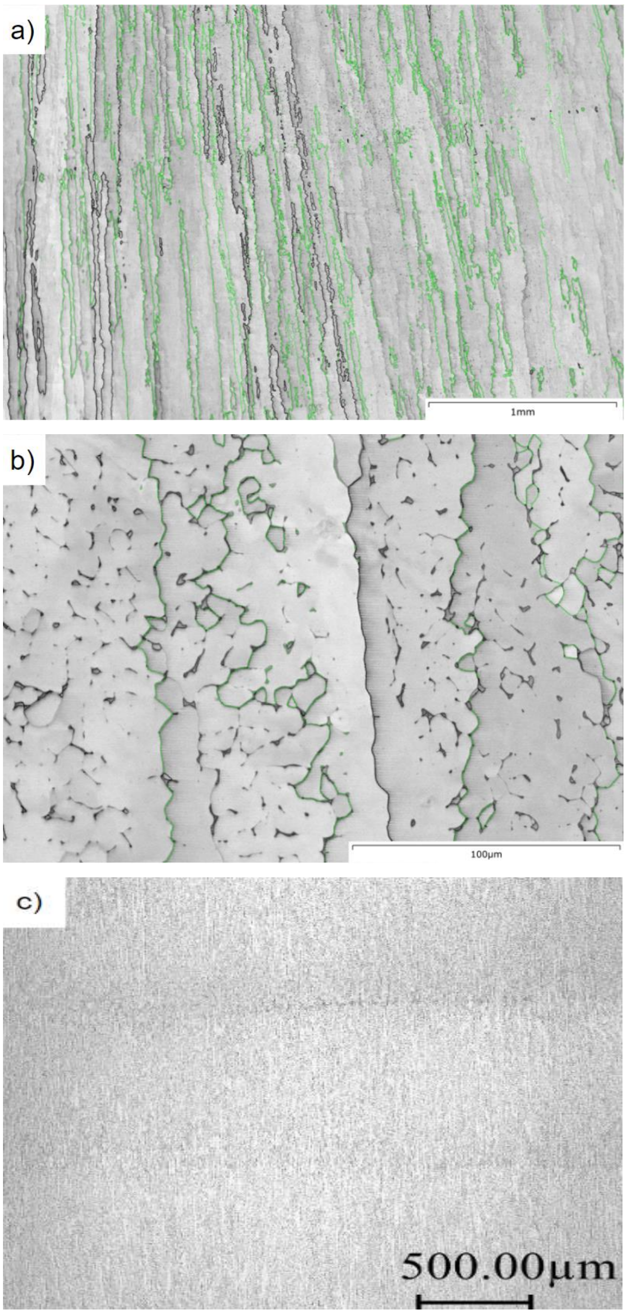
A. Micro and macrostructure

The EBSD images (Fig. 2a and b) revealed that due to high heat input, the remelting of each consecutive weld layer caused epitaxial grain growth in the structure, leading to a coarse columnar grain structure. The average width of these columns can be even several millimetres, but some low-angle sub-structures are also present. Higher magnification scans also reveal the presence of body-centered cubic phase (BCC), which in this instance is most likely delta-ferrite, that has formed to the edges of the dendrite arms during the solidification.

In the WAAM 316L macrostructure in Fig. 2c and d, the deposited layers, and the boundary between them are clearly visible. The thickness of the layers was not completely uniform, as can be seen in Fig. 2c. The average width of the layers was approximately 4.35 mm. As can be seen in Fig. 2e the width of the layers was not constant. There was no visible porosity in the WAAM 316L as can be seen in Fig. 2c and d. The fact that there is no porosity is good considering the fatigue strength of the WAAM 316L.

B. Hardness and surface roughness

The hardness of the sample made from the WAAM 316L part was measured in the build direction at a distance of 7 mm, as can be seen in Fig. 3. The sample was taken from the middle of the WAAM printed part. According to the hardness measurements, the hardness of the WAAM 316L was homogeneous and the boundaries between the layers visible in Fig. 2 were not different in hardness. The average hardness for the WAAM 316L was approximately 192.1 HV. The hardness measurement results corresponded to previous studies on 316L WAAM printed parts. Vora et al. [10] investigated the mechanical properties of a multi-layered 316L structure manufactured by WAAM. Their observation was that the average hardness of the structure was approximately 180.8 HV.



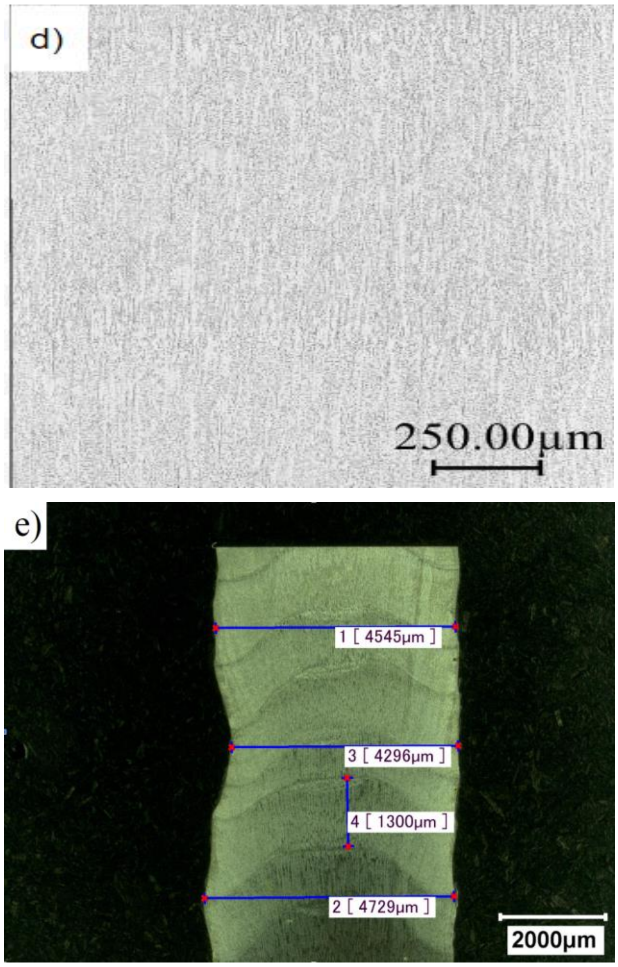


Fig. 2. (a) EBSD map (low magnification), (b) EBSD map (high magnification), (c) Macrostructure longitudinally in deposition direction (low magnification), (d) Macrostructure longitudinally in deposition direction (high magnifigation), (e) Profile of the WAAM printed layers.

The surface roughness of the WAAM 316L was measured to find out if the deposited surface needs to be machined in order to optimize the fatigue strength of the part. The average surface roughness in the build direction was approximately Ra = 62.1 ± 12.9 µm. Based on the results, the surface roughness was relatively high, so machining the part is a good solution in terms of fatigue strength.

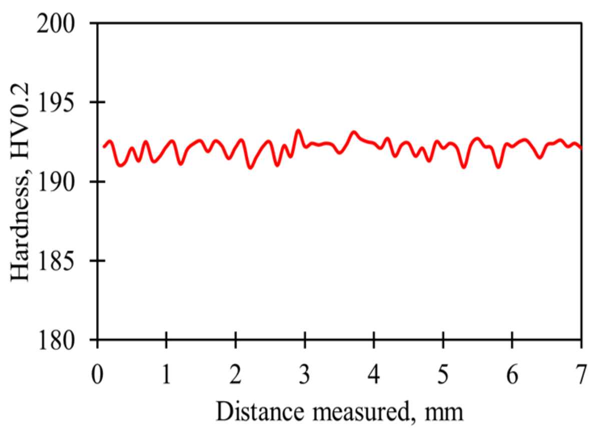


Fig. 3. Hardness measurement of the WAAM 316L in build direction.

C. Tensile tests

The tensile tests were performed on the samples made from the WAAM printed part and the results are shown in Fig. 4. A summary of the mechanical properties obtained in the tensile tests is shown in Table 3. The observation was that the deposited part is not isotropic. Tensile strength in the build direction is approximately 50 MPa (8.8%) lower compared to the tensile strength measured in the deposition direction. The maximum tensile strength was 577 MPa in the deposition direction. The yield strength was approximately 30 MPa lower in the build direction. However, the elongation in the build direction was 23% higher. The yield and tensile strengths were lower than the strengths reported for the welding wire in Table 1. This is because the accumulated heat input in the WAAM process is significantly different from that in welding.

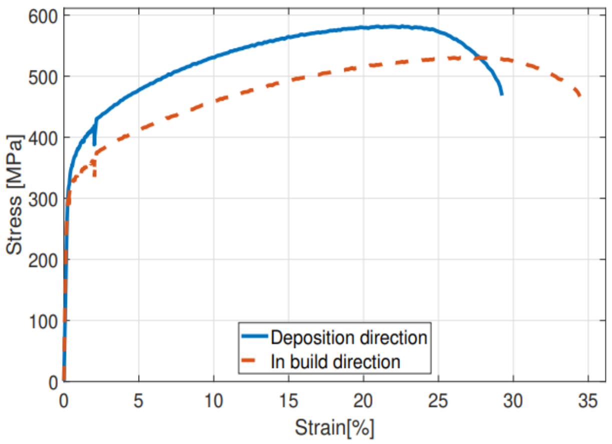


Fig. 4. Tensile strength of the WAAM 316L.

TABLE III. TENSILE STRENGTH OF THE WAAM 316L.

Material	Build direction	Deposition direction
Yield strength [MPa]	302 ± 9.3	333 ± 15.8
Tensile strength [MPa]	526 ± 3.4	577 ± v5.5
Elongation [%]	34.9 ± 0.5	28.3 ± 0.9

D. Fatigue strength

Bending fatigue tests of the WAAM printed 316L were made in the deposition direction and the maximum number of cycles was 2 x 10^6 which was considered the fatigue limit. The results of the WAAM printed 316L bending fatigue tests are shown in Fig. 5. The results have been compared to a 316L sheet metal and powder bed fusion (PBF-LB) printed 316L. PBF-LB specimen surface was not machined (as-build). The results showed that the fatigue limit of the WAAM 316L was 250 MPa which was approximately the same as that of the 316L sheet metal. The fatigue strength of PBF-LB printed 316L was comparable to the WAAM printed 316L and 316L sheet metal in low cycle fatigue regime. However, in the high cycle fatigue regime, the fatigue strength of the PBF-LB printed 316L was significantly lower compared to the WAAM 316L and 316L sheet metal. This is because the PBF-LB 316L printed 316L usually consist of porosity. Porosity affects the fatigue resistance, especially in the high cycle fatigue regime. Jaskari et al. [11] investigated effects of porosity to bending fatigue strength of PBF printed 316L. Their observation was that cracks initiated mainly at the pores and surface quality of the part had no effect on fatigue resistance. The WAAM 316L good fatigue strength can be explained by the fact that there were no pores in the WAAM 316L from which cracks could have initiated, as could be seen in Fig. 2.

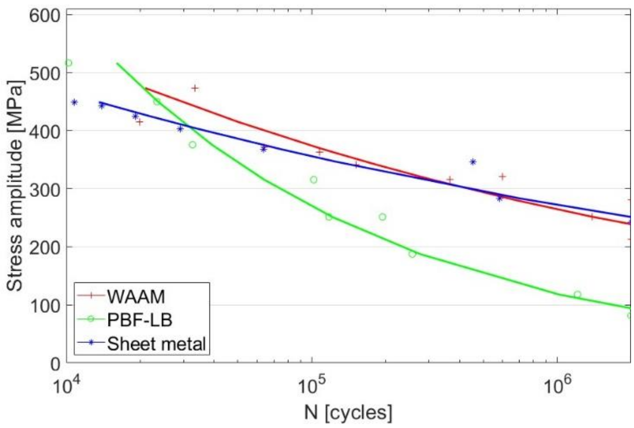


Fig. 5. Bending fatigue strength of the WAAM 316L.

IV. CONCLUSIONS

This paper investigated static properties and fatigue strength of wire arc additive manufacturing ((WAAM) printed AISI 316L. The following conclusion can be drawn:

- The EBSD investigation revealed that due the high heat input of the WAAM process, the remelting of each consecutive deposited layer caused epitaxial grain growth in the structure, leading to a coarse columnar grain structure.
- It was observed that WAAM 316L microstructure examination showed no pores.
- Hardness measurements in the build direction revealed that hardness was homogenous along the structure.
- Surface roughness was relatively high in the build direction, so machining is advised if WAAM printed parts are used in conditions subjected to fatigue loading.
- Tensile strength of the WAAM 316L in the deposition direction was approximately 10.3% higher compared to the tensile strength measured in the build direction.
- Yield strength was approximately 9.6% higher in the deposition direction compared to in the build direction.
- Elongation was 23% higher in the build direction than that in deposition direction.
- Fatigue strength of WAAM 316L was approximately the same as that of 316L sheet metal.
- Fatigue limit of the WAAM 316L was 250 MPa.
- Fatigue strength of the powder bed fusion (PBF-LB) printed 316L was comparable in the low cycle fatigue regime to fatigue strength the WAAM 316L.

- In the high cycle fatigue regime fatigue strength of the PBF-LB printed 316L was markedly lower than fatigue strength of the WAAM 316L. The fatigue limit of the PBF-LB part was 120 MPa.
- Lower fatigue limit of the PBF-LB printed 316L was due to the higher porosity of the part.

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