ADDITIVE MANUFACTURING AND PROPERTIES OF THIN WALLS PRODUCED OF STAINLESS STEEL

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Abstract

The paper deals with the manufacturing of thin walls by various additive technologies. CMT- and microMAG-based WAAM (Wire Arc Additive Manufacturing) and LMD (Laser Metal Deposition) were selected as representatives to produce thin walls. Walls of AISI 316L (austenitic stainless steel) with a height of 100 mm were made by each of the above-mentioned technologies. The geometry and materials properties of the walls were analysed. Tensile strength of specimens, cut-off in the direction of the deposition and perpendicular to deposition direction as well were investigated. Higher tensile strength was observed in samples manufactured in deposition direction. Wall thickness and microhardness on the cross-section were measured. The microstructure was analysed with a light microscope in the unetched and etched stage. The narrowest wall was observed in the case of LMD due to lower heat input. Application of LMD resulted in formation of fine dendritic microstructure. Furthermore, the amount of delta-ferrite was lower in comparison to WAAM deposited walls.

Keywords: Additive manufacturing, stainless steel, laser metal deposition, WAAM, thin walls.

1. INTRODUCTION

Additive manufacturing is a subgroup of manufacturing technology. It is a modern field that is growing in importance. Many different technologies fall under additive manufacturing. A common characteristic of additive manufacturing is the creation of components in layers. However, how the layers are created varies depending on the technology [1-3]. The one group of additive manufacturing is the direct metal deposition (DED), which includes both Wire Arc Additive Manufacturing (WAAM) and Laser Metal Deposition (LMD) technologies. WAAM technology works on the principle of creating a layer of material using wire that is melted by an electric arc [2, 4]. WAAM is used to produce larger, less complex parts [5]. LMD technology works on the principle of forming a layer by melting powder or wire with focused lasers. LMD can be applied for the production of more complex shape components [2, 6]. Heat accumulation during production of walls with higher thickness belongs to main issues in DED, lower heat input additive manufacturing technologies were selected within this study. It is expected that applied technologies could result in decrease the wall thickness and refinement of the microstructure.Manufacturing process of thin-walled structures with WAAM has been discussed by many authors such as Ding et al. [7] or Rahmani Dehaghani et al. [8], who optimized the geometry of thin walls manufactured with WAAM technology. They found that the stability of manufacturing can only be stated after 5 to 10 layers have been manufactured and they chose CMT-based WAAM technology as a way to manufacture thin walls. Manufacturing of thin walls by LMD technology has also been investigated by many authors. For example, Xinlin Wang et al. [9]. They investigated the properties of thin wall of material AISI 316L depending on laser pulsation. They found the hardness using the continuous laser to be lower than those using pulses, the hardness was in the range of 200 to 300 HV and Liu et al. have also studied AISI 316L material manufactured with LMD technology [10].

The aim of the paper is to analyse and compare the properties of AISI 316L thin walls fabricated with WAAM technology with LMD technology. The results will be used for further research in the field of thin wall manufacturing.

2. EXPERIMENTAL

The experiment was made in three different places. Each wall was manufactured with one technology. This was the WAAM technology, where 2 modifications were chosen. The first modification was a CMT-based WAAM running in fully robotic mode. The CMT modification is considered suitable for manufacturing thin structures [8]. The second modification was microMAG-based WAAM, which was performed in semi-automatic mode. Because of the wire diameter of 0.6 mm, there is an expectation of manufacturing a thin wall. The third technology was chosen LMD (Meltio head), which is suitable for manufacturing thin and complex parts [11].

The CMT-based WAAM wall was manufactured (welding source TransPuls Synergic 3200 CMT) on a Fanuc robot. The base material was in a static position. Movement was performed by the Fanuc robot, which moved in the Y-axis direction and after each layer, there was an automatic elevation in the Z-axis by a predefined parameter.

The wall manufactured with LMD technology was also manufactured with a Fanuc robot. There was not the welding torch but a MELTIO head (Meltio Engine Robot integration) for laser manufacturing. Otherwise, the workplace configuration was the same as for the CMT-based WAAM manufactured wall.

A different workplace configuration was chosen for the microMAG-based WAAM technology. The welding torch was in a static position. The base material was moved linearly. After each layer, the torch was elevated in the Z-axis by a predefined parameter. Sigma Galaxy (Migatronic), IAC™ was used as welding source.

The metallographic specimens were cut on a Labotom 3 (Struers) saw and pressed in a CitoPress 1 (Struers). Preparation of the metallographic specimens was done on a Phoenix Beta metallographic grinder/polisher with a Vector automatic head (Buehler). Analysis of the metallographic specimens was performed on an Axio Observer Dm1 light microscope (Zeiss).

AISI 316L (austenitic stainless steel) wire was used to deposit the thin walls. Walls with a height of 100 mm and a minimum width of 90 mm were produced. Different manufacturing parameters were chosen for each technology. The individual parameters are shown in **Table 1**.

The microhardness was measured on an Indentamet hardness tester. Tensile testing was carried out on a LabTest 5SP100 testing machine. The test specimens for the tensile test were taken in the direction of deposition (0°) and in the direction perpendicular to the deposition (90°). The results of the tensile tests carried out are given below (**Table 2**).

Table 1 Manufacturing parameters for each technology

Technology	Voltage (V)	Current (A)	Wire diameter (mm)	Wire feed speed (m/min)	Travel speed (cm/min)	Laser power (W)
CMT-based WAAM	11.6	70	1	2.9	40	-
microMAG-based WAAM	17.1	70	0.6	4.3	26	-
LMD	-	-	1	0.9	60	850

3. RESULTS AND DISCUSSION

3.1. WALL THICKNESS

The wall thickness was measured at the cross sections of each wall. The transverse section was grinded and polished. The wall thickness was measured at the top and middle of the wall (**Figure 1**).

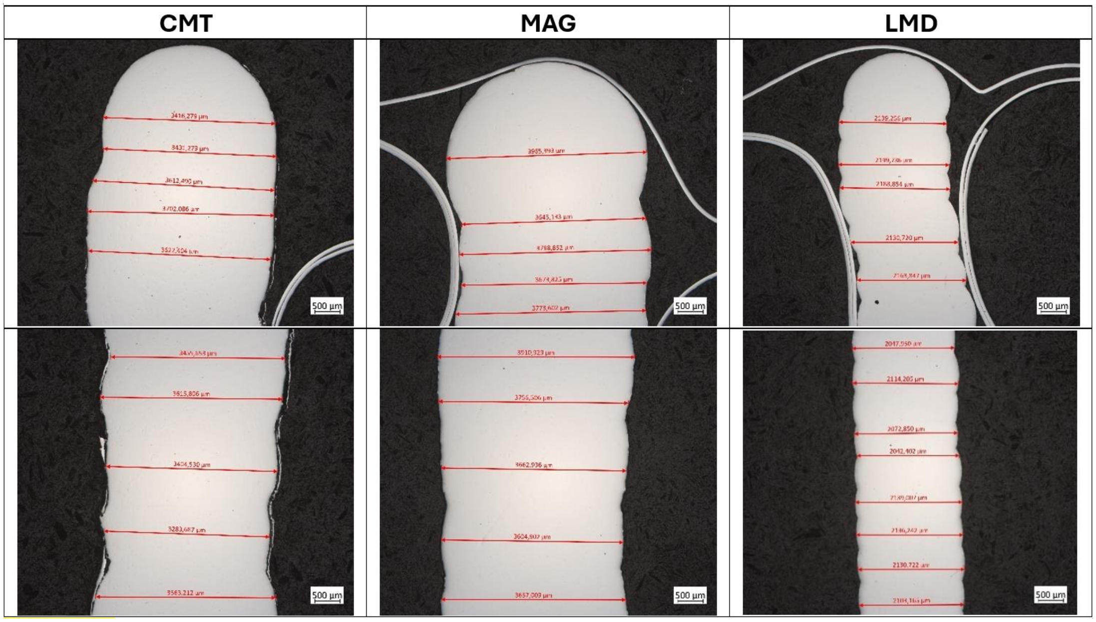

Figure 1 Method of measuring the wall width at the top and middle of the wall for each technology

The middle part of the wall was 0.1 mm narrower than the top part for all walls. The thinnest wall was produced with LMD technology. An average wall thickness of 2.1 mm was achieved. The average wall thickness of the walls formed with WAAM technologies was significantly higher in comparison to LMD (CMT-based WAAM 3.5 mm and microMAG-based WAAM 3.7 mm) (**Figure 2**).

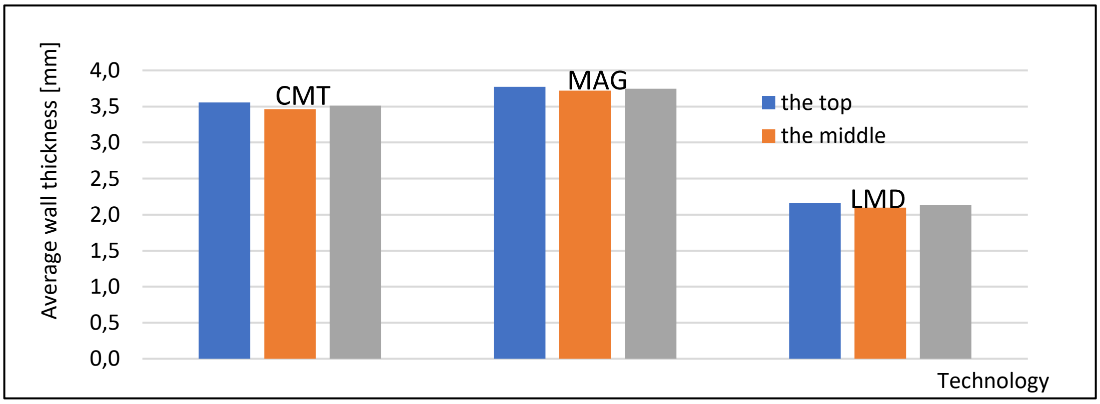

Figure 2 The wall thickness for each technology

3.2. MICROSTRUCTURE

After measuring the wall thicknesses, electrolytic etching was carried out and the microstructure was observed by use of light microscope (**Figure 3**).

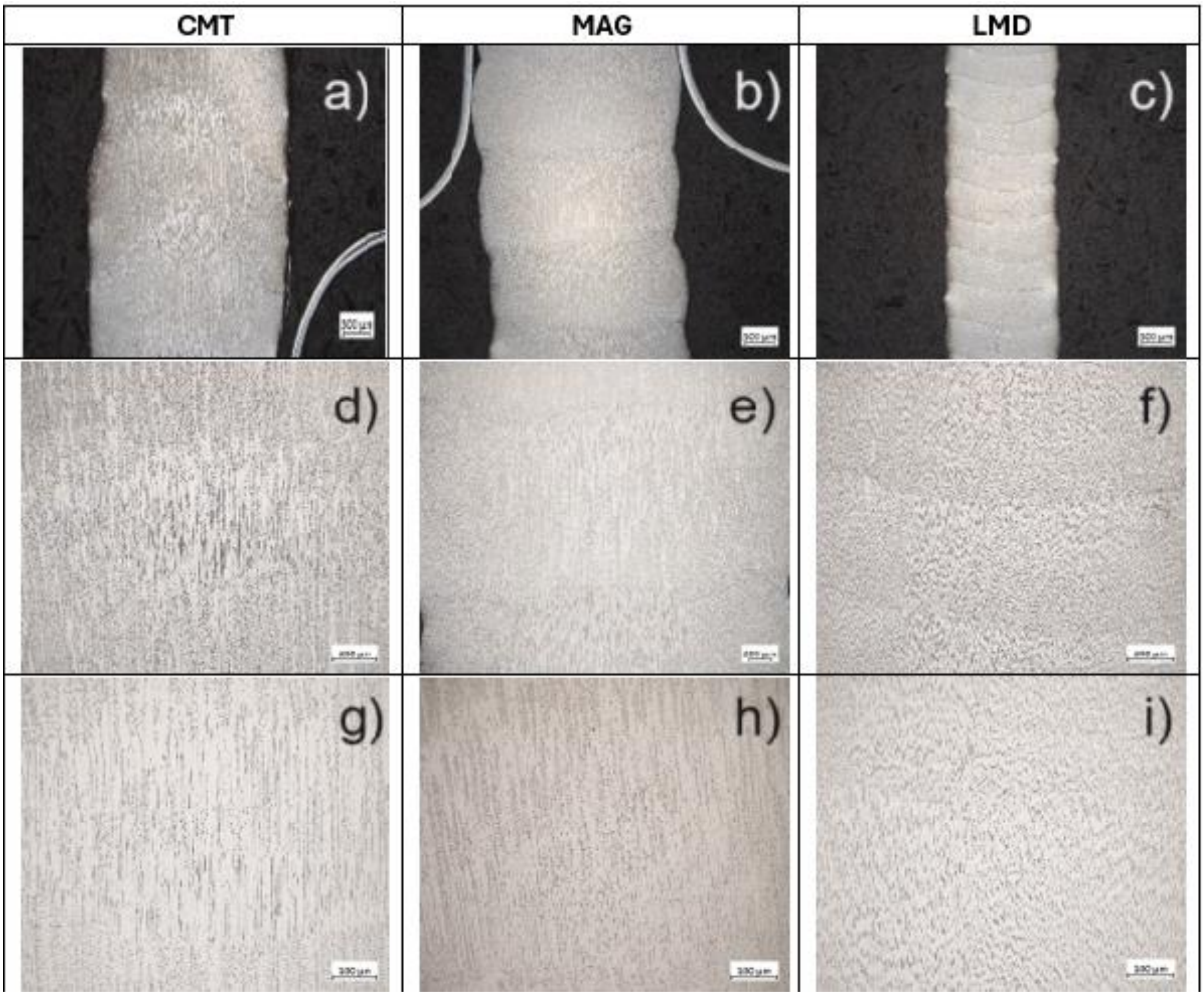

Figure 3 The microstructure of walls for each technology (25x (a-c), 100x (d-f), 200x (g-i))

The microstructure was austenite. Composed of dendritic grains stretched in the direction of the solidification temperature gradient. All technologies produced walls with a fine-grained structure. The finest structure was produced by the LMD technology, which is related to the lowest heat input by this technology (calculated 85 J/mm). CMT-based WAAM technology achieved the most homogeneous structure. LMD technology is characterized by significant heterogeneity at the boundary of individual layers, which may result in a reduced reverse plasticity.

3.3. MICROHARDNESS

The microhardness was measured in the wall axis (**Figure 4**). The average microhardness was similar for all three technologies. For the CMT-based WAAM technology it was 176 HV1, for the microMAG-based WAAM technology it was 189 HV1 and for the LMD technology it was 187 HV1. The measured microhardness of the manufactured walls for all three technologies was lower for the AISI 316L than was measured by Xinlin Wang [9].

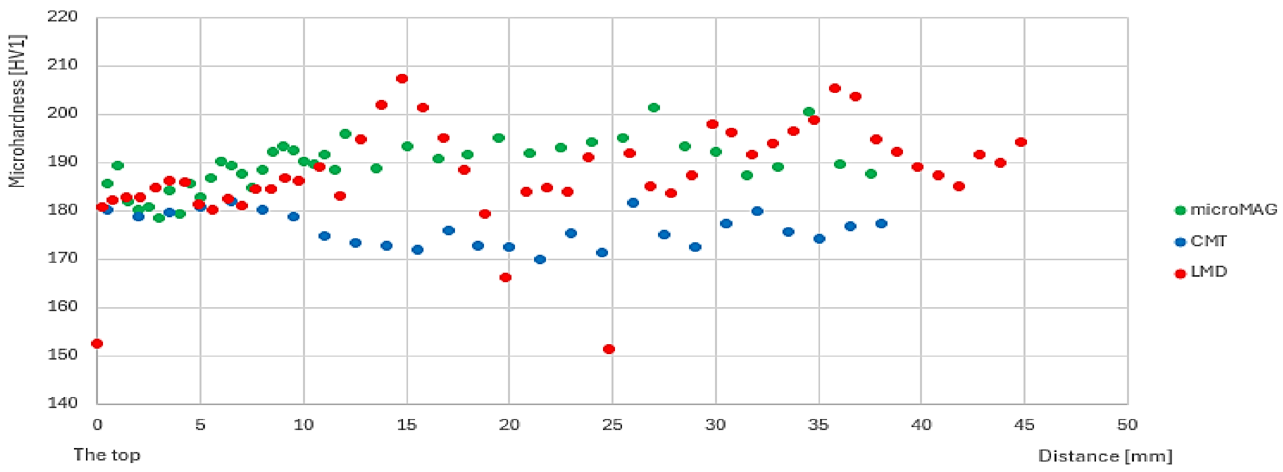

Figure 4 The course of microhardness across walls height for each technology

3.4. TENSILE TESTING

Table 2 The results of the tensile tests

Technology	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)
1 CMT-based WAAM 0°	350	566	38.3
1 CMT-based WAAM 90°	267	701	29.3
2 microMAG-based WAAM 0°	389	649	43.2
2 microMAG-based WAAM 90°	365	658	34.7
3 LMD 0°	469	686	27.2
3 LMD 90°	476	677	35.5

The tensile testing results confirmed the anisotropy of the mechanical properties. The proof strength values $R_{p0.2}$ and the ultimate strength values R_m were different for each technology for the (0°) and (90°) specimens. Only for the LMD technology the ultimate strength was higher for the (0°) specimens. WAAM technologies showed higher ultimate strength in the direction perpendicular to the manufacturing direction (90°). The smallest reverse plasticity, which means the largest value of $R_{p0.2}/R_m$ ratio, was found for the specimens formed by the LMD method. This phenomenon is related to the lowest heat input and the finest microstructure.

4. CONCLUSION

Walls made of AISI 316L using three different technologies were successfully manufactured and subsequently analysed. The wall thickness of the manufactured walls for the WAAM-based technologies was very similar and was around 3.5 mm, however, the wall manufactured with the LMD technology was substantially thinner and its thickness was around 2.1 mm.

The microstructure of all walls was austenitic, consisting of dendrites. The wall manufactured with LMD technology showed the finest structure, which was due to the lowest heat input.

The microhardness of all walls was measured to be very similar (about 180 HV1), suggesting that the chosen technology did not have a significant effect on the resulting microhardness of the walls.

The tensile test showed anisotropy in the wall properties. The values of ultimate strength and proof strength were different according to the direction of the test specimens (0° and 90°) for each technology.

The most significant anisotropic properties were found for the wall manufactured with the CMT-based WAAM method. The walls manufactured with LMD technology showed the lowest ductility and reverse plasticity.

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