Investigation of Mechanical Properties of Aluminum Alloys Produced by Wire Arc Additive Manufacturing Method

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Research Article

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Abstract

Additive manufacturing technology is a new technology that is considered to be a technological revolution in the manufacturing industry. It has advantages such as design flexibility, saving material and time, producing low-density and high-strength parts. Due to these advantages it is used in many sectors such as aviation and automotive. The additive manufacturing method can be integrated into different welding methods. One of these technologies is wire arc additive manufacturing (WAAM). Metal inert/active gas (MIG/MAG) or tungsten inert gas (TIG) welding methods are generally used in this method. The basic principle of the WAAM method is to melt the raw material in the form of wire with electric arc heat and deposit it in layers on top of each other. The fact that large-sized and complex parts can be produced without any problems, almost no waste, and being economical compared to other metal additive manufacturing methods has made this technique a demanding production method.

In this study, AA5356 aluminum alloy wires with a diameter of 2.4 mm were deposited on plates under argon gas by TIG welding method and jointed aluminum parts were produced with different welding parameters. As a result of tests and microstructure investigations, it was determined that the samples prepared parallel and perpendicular to the weld seam direction showed different behavior in terms of mechanical properties. These results were supported by the microstructure and compared with the parts produced by traditional methods. In addition mechanical tests and microstructural examinations were supported by EBSD, EDS and AFM analyzes.

1. Introduction

AM is the process of producing three-dimensional objects by depositing layer by layer. This technology which largely eliminates the design and production restrictions of traditional production methods, has many superior features. Thanks to its design flexibility, it can produce complex shaped parts with a single method. Thus it can reduce the time to market the parts. The scarcity of scrap materials saves weight and saves time and cost. AM technology has different methods that can be classified among themselves and used for different materials and applications. Some of the most commonly used methods are stereolithography, powder bed fusion techniques, material extrusion etc. The fact that it can be used for different materials and applications has made this method popular in many sectors. Parts produced with AM are thin layers of material and joining these layers can be accomplished by different welding techniques. Some of these welding techniques are MIG/MAG, TIG, friction stir welding, ultrasonic welding and laser beam welding [1–6]. Among the different AM techniques, WAAM is one of the most popular applications in recent years. Thanks to this method, large metallic parts with high deposition rates are produced. The WAAM technique can be applied to stainless steel, aluminum, titanium and nickel alloys. Aluminum alloy is widely used in many fields, especially automotive and aerospace, due to its excellent fatigue properties, low density and superior corrosion resistance. Hence the use of the WAAM process in Al components has become remarkable. In recent years, many studies have been carried out on the production of al alloy parts with the WAAM process and the metallurgical and mechanical properties of these parts [7–12]. In one of these studies, Geng et al [13] built straight walls from 5A06 aluminum alloy using the GTAW technique. They examined the tensile strength of these parts and the anitropy in tensile strength. They also observed the effect of welding angle on the weld. At the end of the study, they stated that anisotropy was observed in the parallel and vertical directions and the tensile values of the samples in the vertical direction were lower than the parallel ones. They also contributed to next studies for the optimization of the parameters. Each of the parameters is important in the WAAM process of aluminum.Therefore there are various studies examining the effects of the parameters. One of them, Ayarkwa et al [14] was investigated the effect of alternating current time cycle on microstructure and mechanical properties. They stated that the increase of the alternating current cycle did not have a great effect on the mechanical properties, but increased the grain size and the number of pores. In another study, Horger et al [15] produced parts with the WAAM process using AA5183 aluminum alloy. The hardness values of these parts were compared and their microstructures were examined. The increased temperature with the accumulation of layers caused cracking of the sample. Although this does not affect the strength value, porosity is a common problem in aluminum. Many studies have mentioned the problem of porosity in the WAAM process of aluminum alloys. Various methods have been tried for solve this problem. For instance, Fu et al [16] examined the relationship between hot wire arc and porosity. They reported that the porosity decreased with the increase of the current, and the increase of the current significantly improved the mechanical properties. However the optimization of the parameters has not been done yet. Another common problem is oxidation. Oxidation affects defects such as pores and cracks caused by remelting processes.Therefore many studies are carried out to solve problems such as porosity caused by the oxide problem. Oyama et al. [17] adjusted the modification of the heat source for each layer of the Al alloys produced by the CMT (Cold Metal Transfer) technique and stated that the deposition strategies are important for the success of the method. Many researchers conduct experiments and adopt process modifications to improve the mechanical and microstructure properties of Al and its alloys [18]. In short, WAAM has become the preferred method for Al alloys, but there are still insufficient information on the mechanical and microstructures properties of parts by WAAM process in literature. This study focussed on the effect of the this prosess and microstructural properties were investigated and supported by analyzes. Our study gives a new perspective to the research of the challenges and advantages of WAAM process.

2. Materials And Methods

2.1 Materials

In this study, AA5754 aluminum alloy was used as the substrate 2.4 mm diameter ER5356 aluminum alloy wire was chosen as the filling material. The compositions of the ER5356 wire and AA5754 substrate are shown in Table 1. Before starting production with the WAAM process, the surface was mechanically cleaned. First, the surface was precisely sanded and then cleaned with acetone.

Table 1. Chemical composition of the ER5356 welding wire and AA5754 substrate [19].

2.2 WAAM Process

The main process of the WAAM method involves welding the layers on top of each other. Firstly, it is welded on the base material, after a certain cooling period, it is welded again on the first layer. A wall is built by welding the layers on top of each other. Working principle of WAAM was shown in Figure 1.

Fig. 1 WAAM process

90 (Sample 1) and 105 (Sample 2) amper (A) were used for current values. Wire feed rate was 0.7 m/min and travel speed was 320 mm/min. Flow rate of %99.99 Argon was 12 lt/min. Arc voltage was 14-18 V and arc height was 5 mm. The parameters are shown in Tablo 2. These parameters were chosen as the optimum values after preliminary experimental studies.

The dimensions of sample 1 were 105x64x7 mm, while the dimensions of sample 2 were 120x70x10 mm. In sample 1, 90 layers were deposited and each layer thickness was approximately 8 mm. In sample 2, 120 layers were deposited and each layer thickness was about 6 mm. As the current value increases the layer thickness decreases. The interlayer cooling time was 30 s under argon shielding. Sample 2 is shown in Figure 2. The sample 2 is shown in Figure 2a) before it is milled. After the WAAM process, the surfaces of the samples were smoothed by milling machine and flat samples were obtained as seen in Figure 2b).

Fig. 2 Samples; a) The AA5356 wall produced by the WAAM-TIG process b) Milled 5356 straight wall.

3. Mechanical Characterization

Four horizontal and three vertical tensile samples were taken from the samples at 4 different height levels. Tensile test specimens were prepared by wire erosion cutting method in accordance with ISO 6892-1-2009 standard [20]. Tensile samples are taken parallel and perpendicular to the weld direction and part taken for microstructure and microhardness analysis [21, 22]. For microstructure and microhardness analysis, a piece was taken from the middle of the tensile samples. In this way, microhardness change between layers and microstructure analysis were performed as given in Fig. 3. Schematic appearence of tensile samples are shown in Fig. 3a). The samples produced by wire erosion are given in Fig. 3b). Microhardness test was performed with 200g load 15s application time. The tensile test was carried out at 5 mm/min, at room temperature, with a universal type tensile test machine [23]. Optical microscope, SEM were used to examine the microstructure and EDS, XRD, EBSD and AFM analyzes were performed.

Figure 3 Tensile test specimens; a) Schematic appearance of the samples b) The samples produced by wire erosion

4. Results And Discussion

4.1 Tensile Properties

The average tensile value of the samples taken as sample 1 horizontally is 255.3 MPa and the average tensile value in the vertical is 166 MPa. While the average elongation value of the samples in the horizontal direction is %40, the elongation value of the samples in the vertical direction is %16.3. As a result of the tensile test, the horizontal tensile value of 258 MPa and the vertical tensile value of 160 MPa were obtained for sample 2. The average elongation of the horizontal samples is %37 and the vertical is %18. It is close to the mechanical properties of ER5356 welding wire [24]. ER5356 has yield strength is 110-120 MPa, tensile strength is 240-296 MPa and elongation is %17-26. The results obtained are close to other studies. Köhler et al [25] produced 5356 and 4047 aluminum alloys using pulsed cold metal transfer (CMT-P). The walls produced from these aluminum alloys were compared with each other. In both parts, they observed that the tensile strength in the horizontal direction was higher than the vertical. The difference between the mechanical properties of the horizontal and vertical tensile specimens are shown in Figure 4.

Fig.4 Horizontal and vertical tensile values of sample 1 and sample 2.

When the tensile, yield and elongation values of the two samples were examined, it was observed that there was no significant difference between them. It can be said that welding performed only in the horizontal direction at sample 2 provides higher strength although there is no significant differences. Horizontal tensile values for both samples were found close to other studies and the tensile value of ER5356. The fact that the tensile and yield strengths in the horizontal direction are significantly higher than those in the vertical is also a situation encountered in other studies [26]. For instance Suryakumar et al [27] produced parts using the waam method with copper-clad steel filler wire and examined their mechanical properties. Similar to Al parts, they have reported that higher tensile strength is obtained in the horizontal direction than in the vertical direction in steel materials too. Fang et al [28] produced 2219 aluminum alloy in different CMT modes. In their study, they stated that higher mechanical properties can be obtained according to the changes in the mode of the CMT method. They examined the mechanical and microstructural properties of the parts according to the mode change. As a result of their studies, they observed that the horizontal tensile strengths were higher than the vertical in almost all modes. They stated that the difference in tensile strength between horizontal and vertical samples could decrease, although the anisotropic property continued with the change of parameters.

When the given examples were evaluated the same result was observed in different materials and different welding methods. This shows that the samples perpendicular to the weld seam direction do not have the same homogeneity and contain microstructural differences. As it is known, in the welding process, each pass is applied in successive passes or in multi-pass welding applications [29]. It makes heat treatment on the previous pass and causes it to be softer. As a result, different microstructural transformations occur due to non-homogeneous heat distribution during multi-pass welding and this affects the mechanical properties.

4.2 Microhardness

In order to examine the hardness variation between layers, microhardness measurements were made from the upper and lower layers of the samples. The results of the microhardness values are shown in Figure 5. Sample 1 had an average hardness of 84 $HV_{0.2}$ in the lower layer, while the hardness value in the upper layer was 101.8 $HV_{0.2.}$ In Sample 2, 105.38 $HV_{0.2}$ was obtained in the lower layer and 109.28 $HV_{0.2}$ in the upper layer. In both samples, higher hardness value was observed in the upper layers. This is due to heat accumulation. As the layers are built on top of each other, the surface of the substrate is exposed to high temperature. As the height increases, the heat accumulation increases as the layers overlap. Heat affects hardness negatively. The top layer cools and heats up faster while the bottom layer cools very slowly. Hence higher hardness values are observed in the upper layers due to the cooling rate. Singh et al [30] investigated hardness of samples in their review article on WAAM process strategies and challenges. They reported that as the deposition rate increased, they obtained higher hardness values in the upper regions.

Fig.5 Vickers microhardness of WAAM AA5356 samples

4.3 Microstructure

The biggest difficulties encountered in the production of aluminum alloys with WAAM are the appearance of faulties such as pores, cracks and oxidation. Process parameters such as voltage, current, wire feed speed, interpass temperature, shielding gas flow, and others can alter the effects of oxidation and other problems. The effects of oxidation change the properties of the material, such as mechanical properties, which affect part quality. Although these effects are tried to be minimized by optimizing the parameters, many studies have stated that this problem is inevitable for the production of aluminum alloys by the WAAM process. For example, Hauser et al [31] investigated the oxidation problem in the production of AW4043/AlSi5(wt%) by the waam process. They supported experimental observations with CFD (Computational Fluid Dynamics) simulation. They examined the effects of parameters on oxidation formation and reported that the thickness of the layer varies depending on the change of the CMT mode. By optimizing the parameters, the effect of oxidation can be reduced but oxidation is inevitable in the production of aluminum by this method. Also Ding et al [32] investigated the optimization of the oxidation problem in waam and the effects of surface oxidation. They revealed that oxidation does not only affect the mechanical and microstructural properties. Surface oxide can cause problems in the progress of the process affect the deposition rate and reduce the deposition efficiency. Hence oxidation is one of the main problems of this process and oxidation optimization studies are envisaged for the widespread use of WAAM technology in many areas of use.

When heated aluminum comes into contact with the ambient air and the oxygen it contains, a strong aluminum oxide layer (Al_2O_3) is formed as an exothermic reaction. Al_2O_3 is a very durable oxide that gives aluminum its excellent corrosion resistance. While oxides of most other metals melt at or below the temperature of their metals, Al_2O_3 has a very high melting point of 2060 °C, compared to the pure metal melting at 660 °C [31]. Hence this situation is frequently encountered in the production of aluminum alloys with WAAM. The oxide layer formed on the parts are given in Figure 6. The microstructures of sample 1 and 2 are shown in Figure 6a) and Figure 6b), respectively. In the microstructure images, the oxide layer on the aluminum parts can be clearly seen. Even if the process is protected by the inert gas, a strong surface oxide is formed when the aluminum which is heated due to the rising heat during welding, comes into contact with the oxygen in the environment. Especially Al-Mg alloys are easily oxidized when heated the high corrosion resistance of 5xxx series alloys is associated with this situation. Easily oxidized 5356 samples were exposed to constant heat input since they were produced by welding on each other. WAAM process accelerated the oxidation process and a surface oxide layer was formed in a short time. EDS analysis of the samples is given in Figure 6c). In the EDS analysis of certain parts of the part surfaces, Al, O and Mg peaks and their weight ratios are seen. In accordance with the wire content, 5356 Al alloy contains more than 5% Mg. Besides Mg, O peaks were observed due to the Al_2O_3 layer formed on the surface of the parts [31,33].

Fig.6 Al_2O_3 layer formed on the surface of the part; a) Sample 1, b) Sample 2, c) EDS analysis.

4.4 Electron Backscatter Diffraction (EBSD) Analysis

In order to examine the effect of the current on the mechanical and microstructure properties of samples, the samples were taken from the top and bottom layers and these samples were analyzed by EBSD analysis. EBSD maps are shown in Figure 7. The coarse grain structure formed in the lower regions of the first layers of Sample 2 is shown in Figure 7a). Upper layers of sample 1 are shown in Figure 7b). Fine grain structures formed in the upper layers of Sample 2 are shown in Figure 7c). Compared to Figure 7b and c, it is seen that the current range has not a significant effect on the grain size. However, grain size differences were observed between the layers as can seen in Figure 7a) and c. Coarse grain structure was observed in the lower layers otherwise fine grained structures were observed in the upper layers [34,35].

Fig.7 Examination of grain structure by EBSD analysis; a) Bottom layers of sample 2, b) Top layers of sample 1, c) Bottom layers of sample 2

EBSD analysis results are in accordance with tensile test results and Hall-Petch rule. Hall-Petch rule was shown in equation 1. Similar results are observed in many studies [36,37]. As the grain size increases, the tensile value decreases. When compared to the upper layers, coarse grain structure and low tensile strength were detected in the lower layers.

$$\sigma_y = \sigma_0 + kyd^{-1/2} \tag{1}$$

4.5 Atomic Force Microscopy (AFM)

The milling operation after the WAAM process only visually helped to obtain a relatively flat surface compared to the initial state of the specimens. When the surface topography was examined, elevations and depressions were found between the source layers as given Figure 8. Surface properties of sample 1 are given Figure 8 a) and sample 2 in Figure 8 b). Since the WAAM technology is based on a multi-pass welding process, the upper part of the previous layer is partially melted during each new layer deposition.

Surface roughness occurs in the part that is formed by coming together from many layers. Since WAAM is an AM method, finishing process are often required and surface roughness can be improved by machining methods such as milling. However in useage areas where surface roughness is an important criterion, it is necessary to optimize the parameters of finishing process or use different methods to improve the surface properties [38,39].

Fig. 8 AFM images; a) Sample 1 b)Sample 2.

5. Conclusion

In this study, the production of AA5356 aluminum alloy with the WAAM was successfully carried out. When the mechanical values of the samples produced at two different currents, 90 A and 105 A, were compared, no significant difference was observed but it was determined that the sample produced at 105 A showed higher mechanical properties. As a result of tensile tests and microstructure investigations, it was determined that the samples prepared parallel and perpendicular to the weld seam direction showed different behavior in terms of mechanical properties. The tensile values of the samples parallel to the weld seam direction, Samples 1 and 2, were obtained as 250 MPa and 258 MPa, respectively. The tensile values of the vertically prepared samples were determined as 160 MPa and 165 MPa, respectively. The reason for this anisotropic behavior is the inhomogeneous heat distribution. In the part formed by welding on each other, each welding pass causes the other to be softer by heat treatment and this affects the mechanical properties. When the hardness test results are examined, it is observed that the microhardness values of the samples change with the change of the deposition height. While the lower hardness value was measured in the samples taken from the lower layers, it was observed that the hardness increased due to the heat accumulation as the upper layers went. However, the mechanical properties of the samples were compared with AA5356 aluminum alloy wire and it was observed that the values were close to each other. In addition, the grain structures of the samples were examined by EBSD analysis and it was observed that the grain structures of the upper layers were thinned by the effect of rapid cooling.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

Not applicable

Ethics approval

Not applicable

Consent to participate

Consented by all authors.

Consent for publication

Consented by all authors.

Author Contributions

All authors contributed to the study design and conception. The necessary steps were determined and the study was planned [Yahya Bozkurt], [Elif KARAYEL].Material preparation, data collection and analysis were performed by [Cezmi ÖZDEMİR], [Murathan KALENDER] and [Elif KARAYEL]. The first draft of the manuscript was written by [Elif KARAYEL] and all authors commented on previous versions of the manuscript and approved the final manuscript.

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Tables

Table 1. Chemical composition of the ER5356 welding wire and AA5754 substrate

Alloys	Si	Fe	Cu	Mg	Mn	Cr	Ti	Al
ER5356	<0.25	<0.40	<0.10	4.9	0.05-0.20	0.05-0.20	0.06-0.20	Bal.
AA5754	0.0-0.40	0.0-0.40	0.0-0.10	2.60-3.60	0.0-0.50	0.0-0.30	0.0-0.15	Bal

Table 2. Process parameters

Parameters	Parameter set
Current range (A)	90-105
Travel speed (mm/min)	320
Wire feed rate (m/min)	0.7
Arc voltage (V)	14-18
Shielding gas flow (lt/min)	12
Arc height (mm)	5

Figures

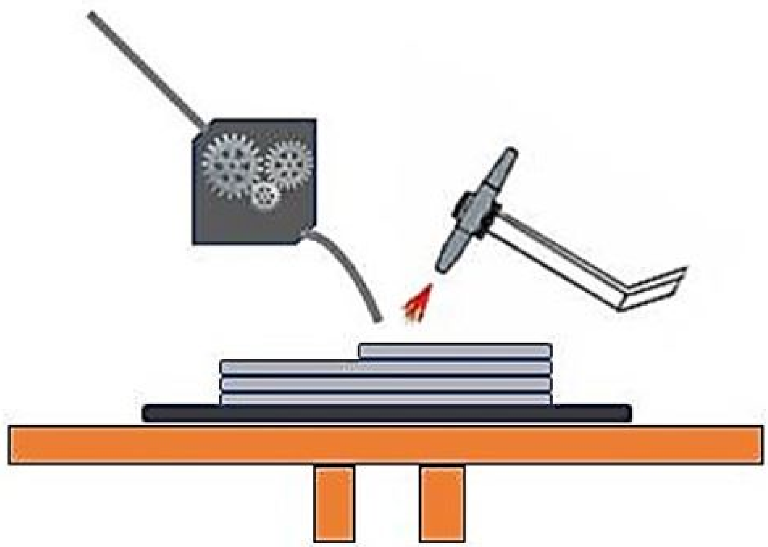

Figure 1

WAAM process

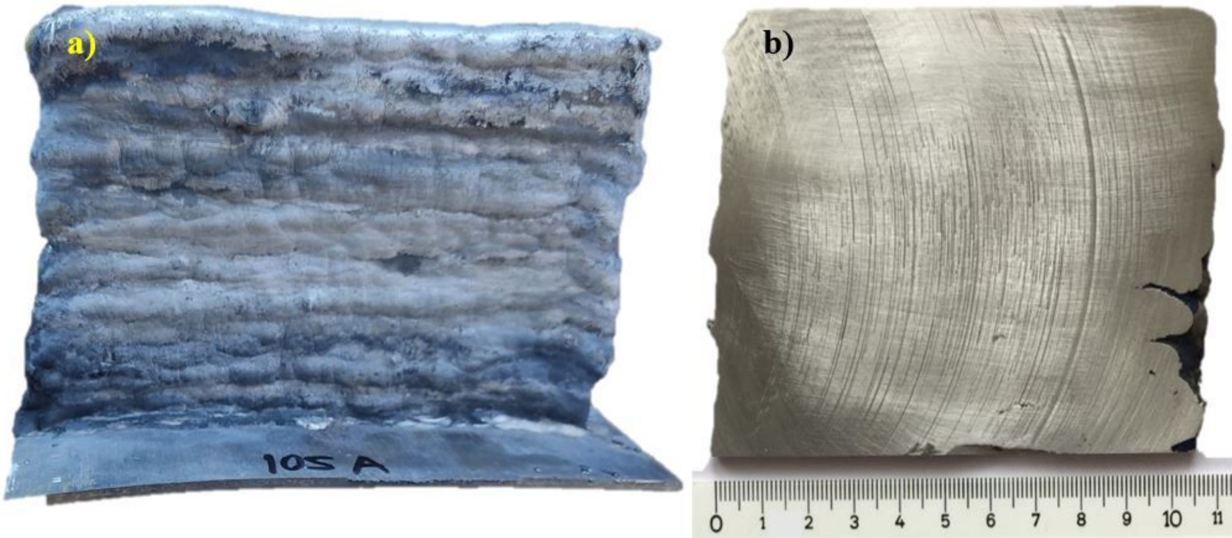

Figure 2

Samples; a) The AA5356 wall produced by the WAAM-TIG process b) Milled 5356 straight wall.

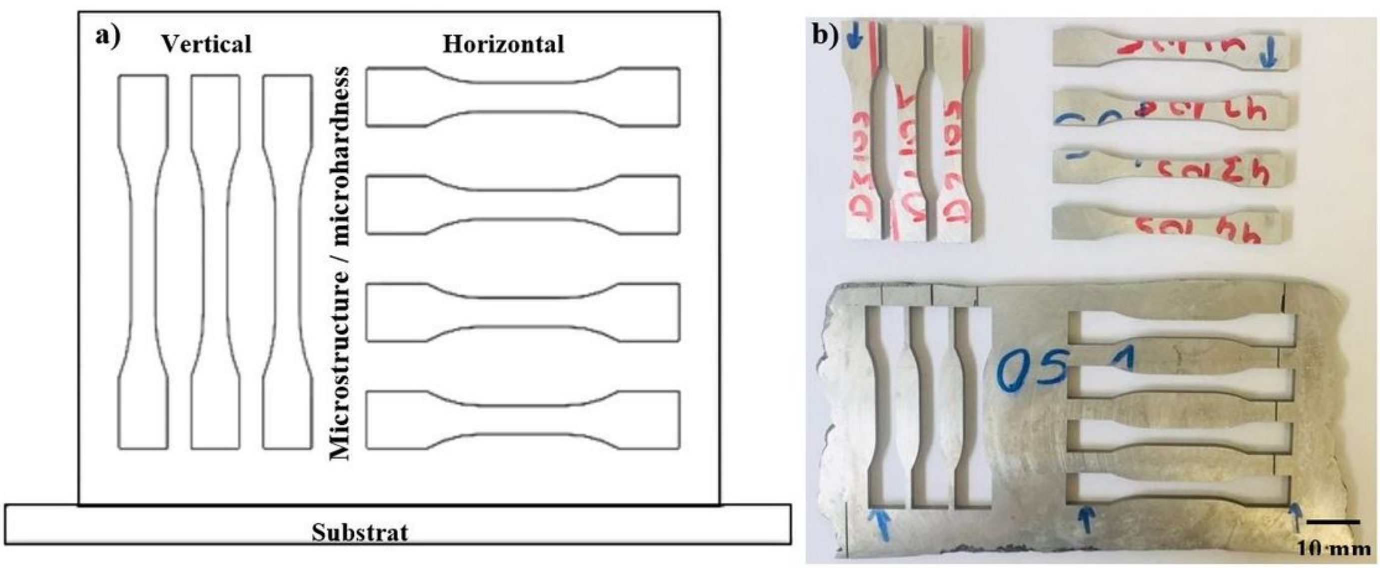

Figure 3

Tensile test specimens; a) Schematic appearance of the samples b) The samples produced by wire erosion.

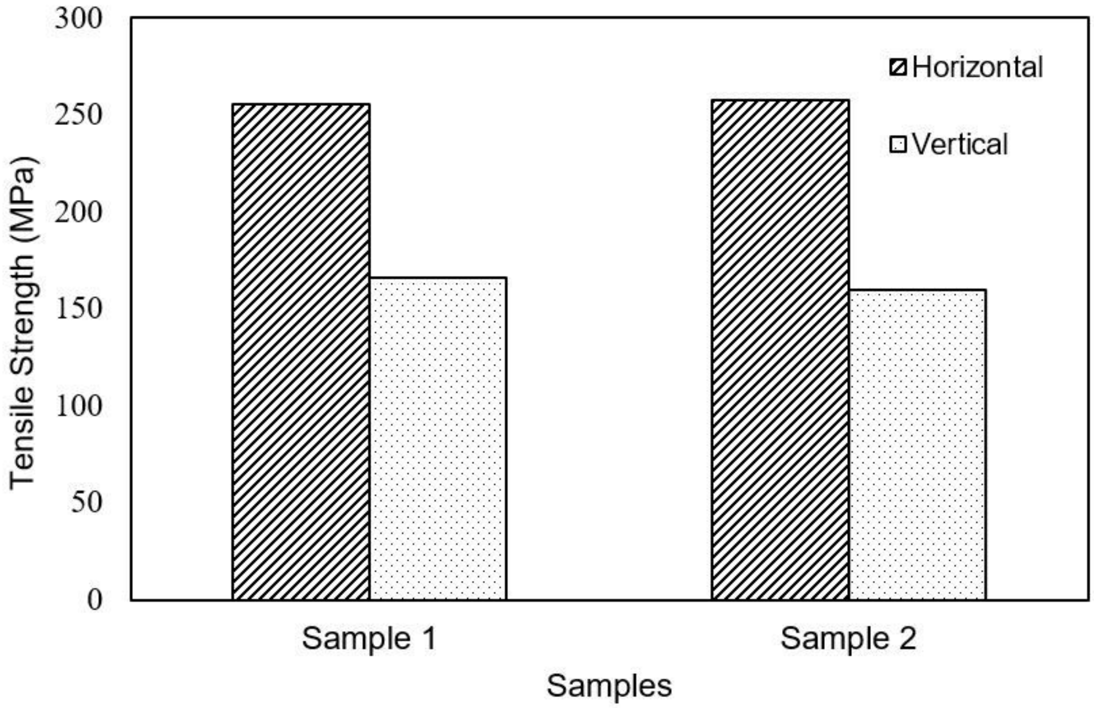

Figure 4

Horizontal and vertical tensile values of sample 1 and sample 2.

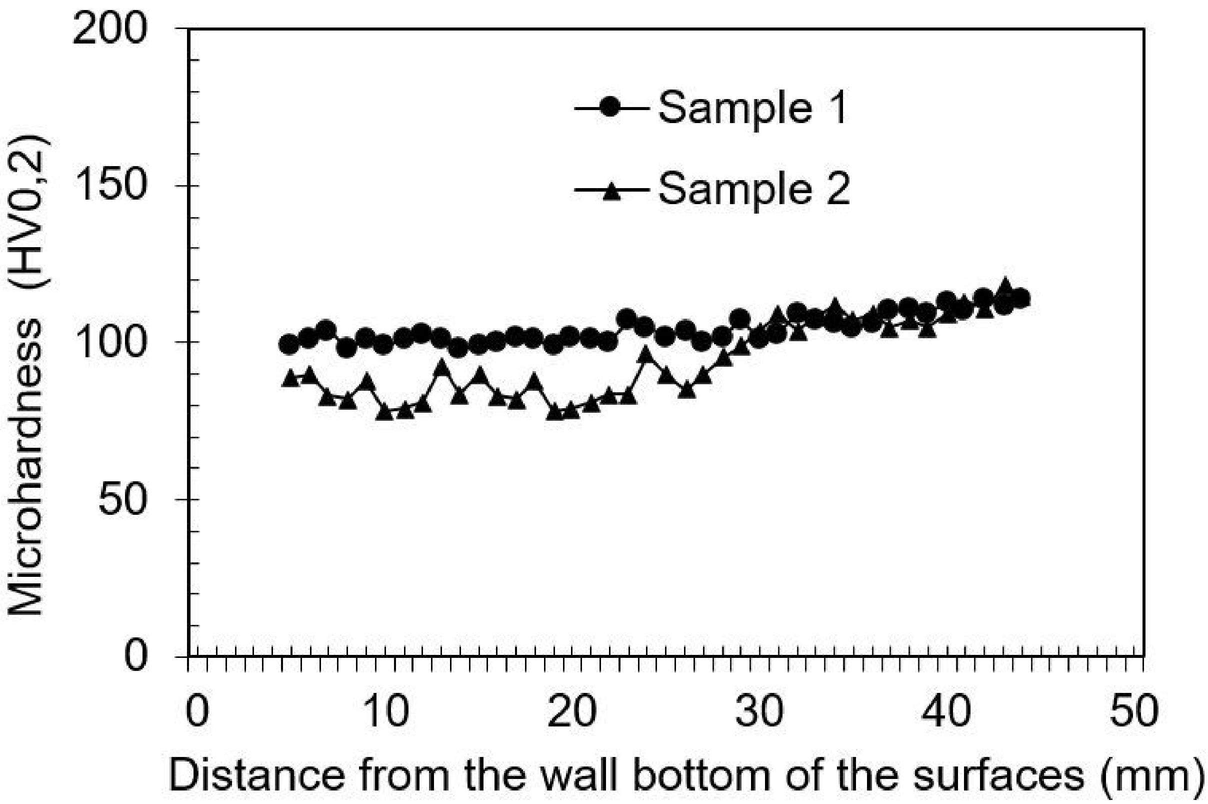

Figure 5

Vickers microhardness of WAAM AA5356 samples

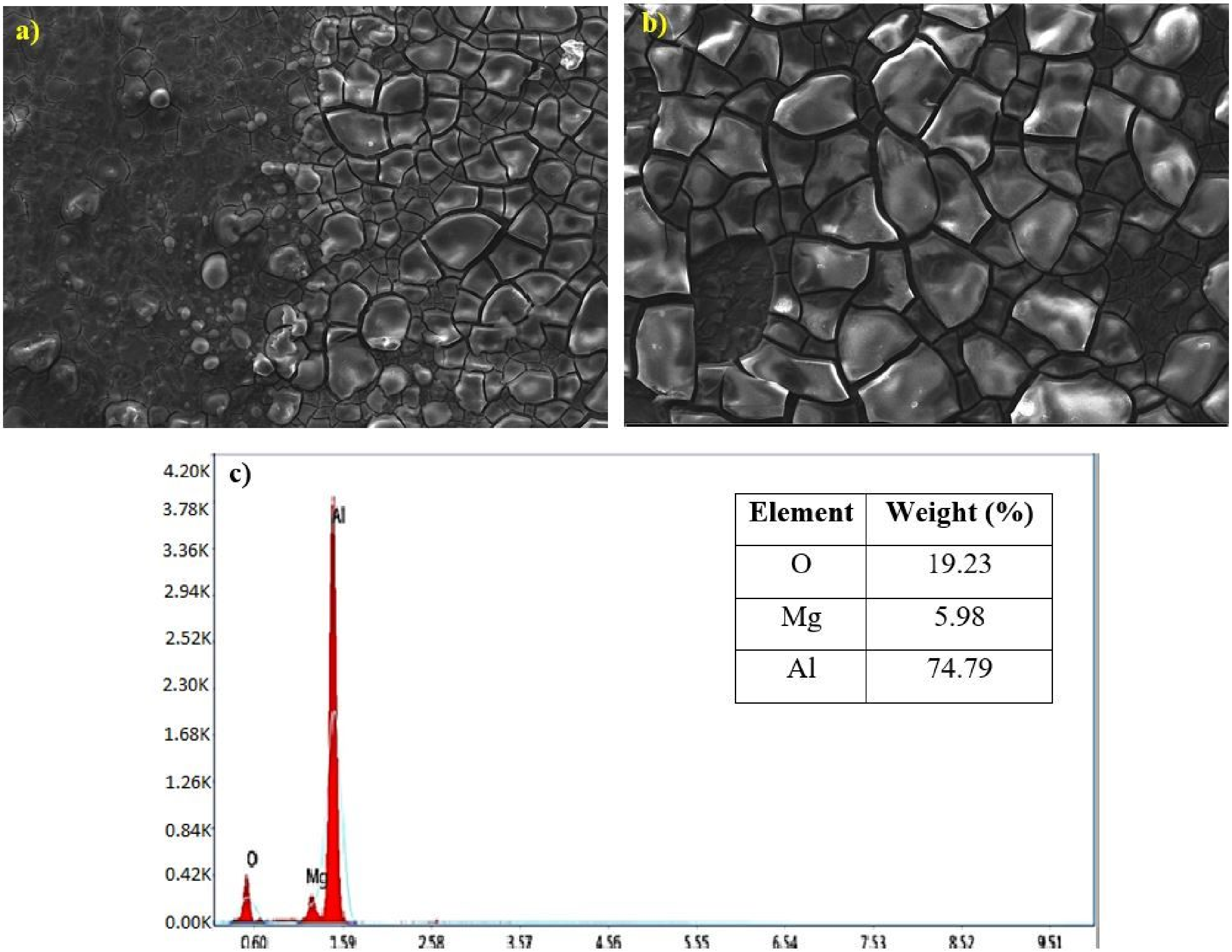

Figure 6

Al_2O_3 layer formed on the surface of the part; a) Sample 1, b) Sample 2, c) EDS analysis.

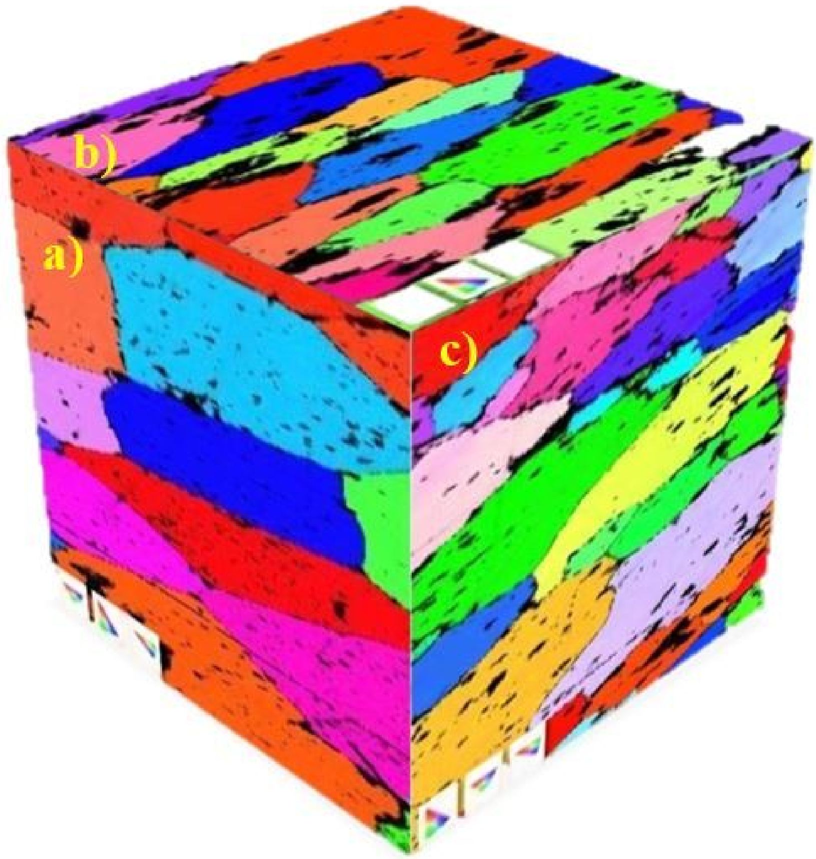

Figure 7

Examination of grain structure by EBSD analysis; a) Bottom layers of sample 2, b) Top layers of sample 1, c) Bottom layers of sample 2

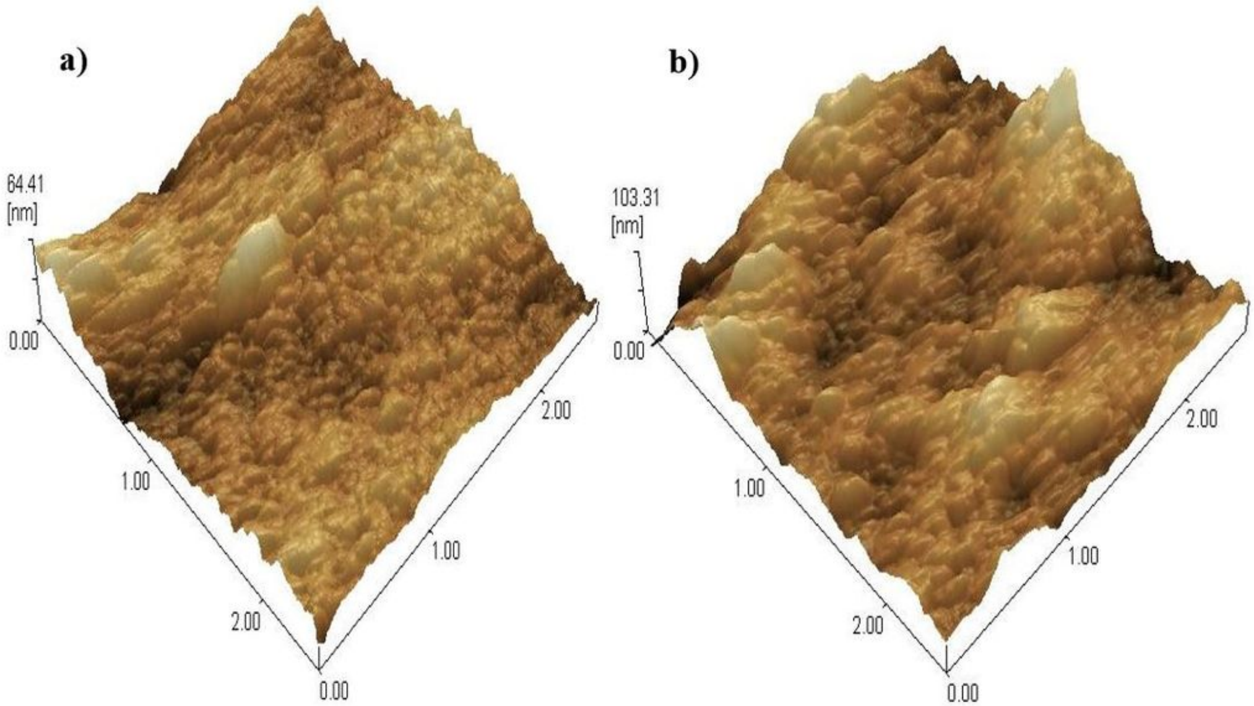

Figure 8

AFM images; a) Sample 1 b)Sample 2.