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Micro-Structure and Properties of Aluminum Alloy Made by Arc Additive of Al-Si Alloy

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Abstract. The silicon element can increase the fluidity of the molten metal and the corrosion resistance of the welding wire in the welding process. The components formed by the accumulation of aluminum alloy wire with different silicon content have different micro-structure and properties. By using TIG welding method and taking ER4043 and ER4047 welding wire as the research object, multi-layer fuses stacking test was carried out on 4043 aluminum alloy substrate. Comparing the micro-structure and mechanical properties of two different welding wire additions, it was found that the grain size and lattice type of 4047 micro-structure were more uniform, and the α-Al phase and Al-Si eutectic phase were mainly formed. In the 4043 micro-structure, α-Al and Al-Si eutectic forms mainly columnar crystals and a small number of reticular crystals. The average tensile strength of 4047 is 35.91MPa higher than that of 4043. The average fracture elongation of 4047 print specimen is 6.72% lower than that of 4043 print specimen. The test shows that the tensile strength of 4047 arc additive is higher than that of 4043 arc additive, but the shape of the component is decreased.

Key words: silicon element; Aluminum-silicon alloy; Additive manufacturing; micro-structure

1. Introduction

At present, additive manufacturing[1] technology has been developing rapidly in the fields of aerospace, biomedicine, electronic products and automobile manufacturing[2]. With the progress of technology, additive manufacturing has a wide application prospect in the manufacture of Marine and ocean engineering equipment, especially in the small batch customization of Marine parts.

Aluminum alloy is widely used in various industries because of its unique physical and chemical properties, especially its strong corrosion resistance and high specific strength. Al-Si alloy[3-4] is widely used in aviation, internal combustion engine, automobile, electronics and other industries because of its excellent castability, good

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weldability, high corrosion and wear resistance. WAAM technology uses arc as heat source, silk as raw material to rapidly manufacture parts and repair parts, and uses additive manufacturing technology to modify the surface of parts, comprehensively improving the mechanical properties of parts and increasing the service life of parts.

In this paper, 4043 and 4047 aluminum welding wires were used as additive manufacturing materials, and GTAW welding was used as heat source. The arc additive components were completed under the same welding process parameters. The micro-structure and properties of additive manufacturing components were studied. The grain differences in the micro-structure of different welding wires were observed by metallography microscope, and the reasons for the different material properties of two kinds of welding wires were studied.

2. Experimental materials and methods

In this paper, OTC-FDV6 welding robot[5] is used to complete relevant experiments. The specification is vertical multi-joint, with 6 basic axes, as shown in **Figure 1.**.4043 aluminum alloy, which is widely used in the substrate, is 275mm×140mm×3mm, and the weld wire is commonly used 4×××× aluminum alloy welding wire (4043 and 4047). The chemical composition of the two welding wires is shown in **Table 1** below.

Table 1. Element composition percentage of ER4043 and 4047 wire

material	Si	Fe	Cu	Mn	Mg	Zn	Ti	others	Al
ER4043	4.5~6	0.8	0.3	0.05	0.05	0.1	0.2	0.15	allowance
ER4047	11.0~13.0	0.8	0.3	0.15	0.1	0.2	—	0.15	allowance

Based on the metal characteristics of 4043 aluminum substrate and aluminum silicon alloy welding wire, GTAW arc additive manufacturing method was used to carry out the wire cladding accumulation experiment. First, the 4043 aluminum substrate was polished to obvious metal luster by an electric Angle mill, the oxide film was removed, and then the surface of the test plate was wiped with absolute alcohol to remove oil and other impurities, so that the wire could be better combined with the substrate. Position the starting position, end position and welding path with the instructor, and finally run the program so that the wire can form a complete weld path on the substrate surface. In order to observe the different micro-structure of two different welding wires, welding process parameters should be kept consistent to ensure the same heat input in the welding process. In this experiment, welding process parameters were selected as current 140 A, arc length 4 mm, traveling speed 300mm/min, and time interval between each layer 10 min. Argon gas was used as welding protection gas. Protection gas flow rate 15 L/min. At the same time, multilayer fuses were stacked to prepare the forming parts. The cross section of the additive was cut by wire cutting method, polished with sandpaper, polished with polishing machine, and etched with Keller reagent (HF+HCl+HNO3+H2O volume ratio 1:1:5:2.5:95) etching solution. Olympus BX51 optical microscope was used to observe the internal micro-structure of the additive wall.

Figure 1. Welding robot and TIG welder

3. Results and discussion

3.1 micro-structure analysis of forming layer

The same arc process parameters were used to carry out the single-pass multi-layer cladding stacking test, as shown in **Figure 2.**.The 80-layer stacking test was completed respectively. The height of the two kinds of walls measured was about 6cm, and the average height of each layer was 0.7~0.8mm. This is mainly due to the higher silicon content in 4047 welding wire, which leads to stronger fluidity of molten metal formed after melting. The surface tension of molten metal is not enough to balance arc force and gravity, and the surface tension of molten metal is affected by temperature. The higher the temperature is, the smaller the surface tension is. The molten wire, attracted by the current, flows more toward the cooler region, creating a hump.

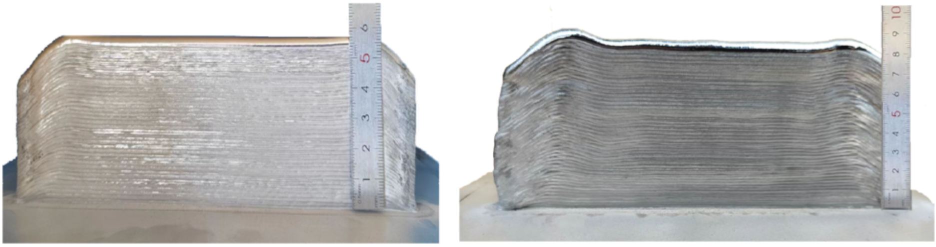

Figure 2. TIG Arc additive 4043 and4047 aluminum alloy wall (The left image belongs to 4043 aluminum alloy and the right image belongs to 4047 aluminum alloy)

It can be found that there are bright fringes distributed in the microstructure, and the fringes approximately exhibit parallel distribution, and the material exhibits layered characteristics. This is because in the process of arc stacking, the newly stacked layer will melt the previous layer again, and different microstructure morphologies are generated between layers. Since arc additive is a periodic process, during welding, The latter layer will remelt the previous layer. Therefore, except for the top pass, the microstructure morphology of the middle layers is similar. For our study, one of the layers is taken out for observation and comparison, as shown in **Figure 3.**, where **Figure 3(a).** and **Figure 3(c).** are the central part of the layer of 4043 additive, and **Figure 3(b) .** and **Figure 3 (d).** are the central part of the layer of 4047 additive.

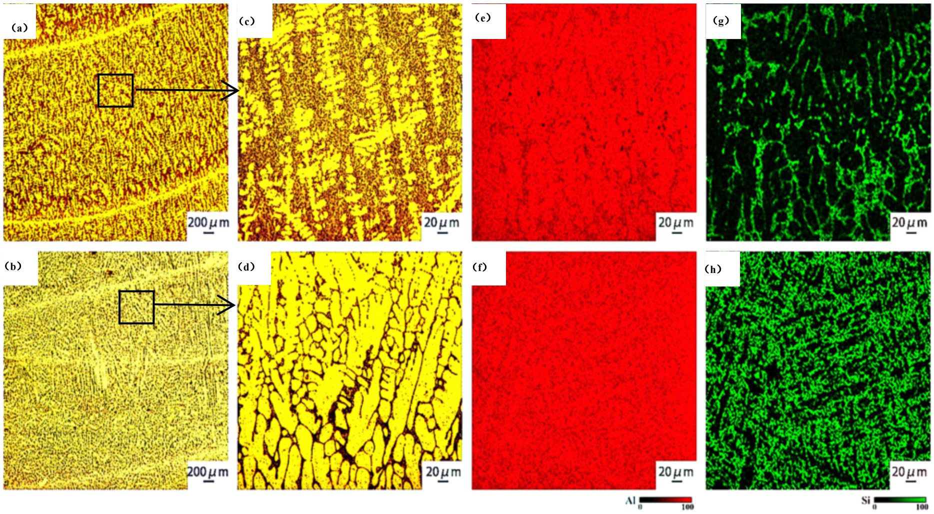

Figure 3. Metallographic (a-d) and EDS scanning energy spectrum (e-f) of the central part of the microstructure layer of 4043 and 4047 aluminum alloys (red area represents Al element, green area represents Si element); (a-b is the 50-fold magnification of metallographic microscope, and c-d is the magnification of metallographic diagram in the box).

According to the analysis of **Figure 3.**, after arc additive forming, alloy 4043 and alloy 4047[6-8] are relatively dense inside, and no metallurgical defects such as microcracks or pores are observed. Moreover, the microstructure of the two kinds of additives is the same, consisting of bright and dark parts, and the bright part has a larger grain, accounting for more in the central part of the layer, while the dark part has a smaller grain. However, they are all clustered together and distributed in the interstice of bright colored parts. The specific metallographic components of bright colored parts and dark colored parts can be determined by energy dispersive spectroscopy (EDS), as shown in **Figure 3 (e-h).**.

Since 4043 and 4047 are Al-Si alloy materials, it is known that there are two kinds of metallographic structures in the central microstructure of the layer. Al-Si alloy will form the basic α-Al initial grain in the process of welding and melting, which is surrounded by Al-Si eutectic phase between the aluminum alloy grain and the grain. The content of Al-Si elements in the two microstructures is measured. The average silicon content in the central area of the microstructure layer of 4043 additive is 5.92%, and the average silicon content in the central area of the microstructure layer of 4047 additive is 13.58%, which is consistent with the silicon content in the welding wire.

The microstructure of 4047 metallographic structure is more uniform, the α-Al matrix mainly presents the form of secondary dendrites, the dendrite growth is more disorderly, no obvious direction, the distribution of large flake and needle eutectic silicon phase in the dendrite gap. There are elongated columnar crystals in 4043 microstructure. These columnar crystals pass through the interlayer fusion line and grow continuously along the direction of additive accumulation. In addition, columnar dendrites grow along the deposition direction of 4043 metallographic structure, and there are a few mesh-like dendritic structures. The microstructure is obviously uneven and can be divided into coarse and fine crystalline regions. Because the TIG welding mode adopts pulse current mode, the high-frequency oscillation of pulsed TIG welding is beneficial to obtain refined grains in the metallographic structure. The rapid decrease of heat input enables the metal liquid to cool rapidly in the welding process, resulting in the formation of a small number of equiaaxial grains. Moreover, the high arc voltage in the pulse current mode makes the grain size finer, which results in the formation of different microstructure in the center of the 4043 aluminum alloy layer[9-10].

3.2 Analysis of mechanical properties of forming layer

By analyzing the tensile strength of 4043 and 4047 additions, the mechanical properties of both can be compared. Two tensile samples are taken in the direction perpendicular to the weld passage and parallel to the weld passage, and the tensile test is carried out by the multifunctional tensile testing machine. The tensile rate is 1mm/min, and the strength and plasticity of the material can be expressed by the tensile strength and fracture elongation.

The comparative test results of different welding wire additions are shown in **Figure 4.** The measured results are analyzed, and the average tensile strength of 4043 additions is 155.74MPa and the average fracture elongation is 19.22%. The average tensile strength of 4047 additive is 191.65 MPa and the average elongation at break is 12.50%. It can be shown that 4047 additive has better strength and worse plasticity than 4043 additive.

Comparing the performance of the same component, it can be found that in the addition 4043 and 4047, the average tensile strength of the component parallel to the weld path direction is 160.07 MPa and 196.02 MPa, while that perpendicular to the weld path direction is 151.42 MPa and 187.09 MPa. It can be considered that the strength properties of 4043 and 4047 additions have little difference in each direction, and the average fracture elongation is larger in the direction parallel to the weld passage than perpendicular to the weld passage, the difference is 3.13% and 5.44%. Therefore, the performance plasticity of the component parallel to the pass direction is higher than that perpendicular to the pass direction.

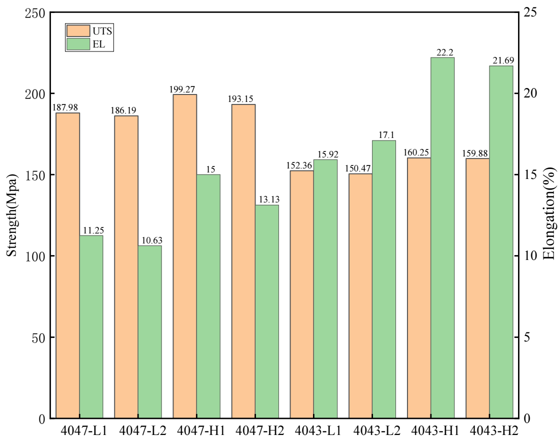

Figure 4. Experimental results of ultimate tensile strength (UTS) and elongation (EL) at break of 4043 and 4047 aluminum alloys,L represents transverse direction, H represents longitudinal direction.

Generally, the problem of anisotropy will occur in the additive forming parts, but the experimental results show that the tensile strength of the additive parts has little difference in the vertical and horizontal directions. The main reason for the problem is that the strength in Al-Si alloy is divided into aluminum matrix strength, Al-Si solid solution strengthening and fine-crystal strengthening. However, grain refinement has little effect on the strength enhancement of materials. There is no directivity between the strength of Al matrix and Al-Si eutectic. From the perspective of grain distribution of metallographic structure, although a single aluminum grain forms a columnar crystal, from the perspective of the entire micro-structure, the crystal direction distribution is more dispersed, and the direction difference is not obvious. Thus, it can be seen that the problem of anisotropy can be ignored in Al-Si alloy additive parts.

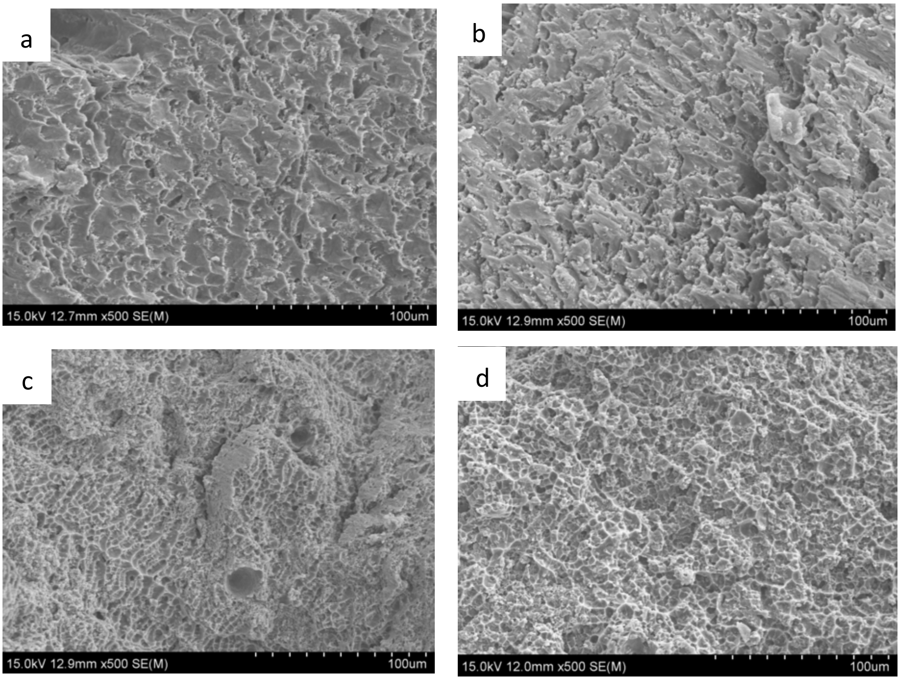

Figure 5. Fracture morphology of 4043 and 4047 tensile parts, (a represents a 4043 transverse tensile fracture, b represents a longitudinal tensile fracture, c represents a 4047 transverse tensile fracture, and d represents a longitudinal tensile fracture).

The tensile fracture of the additive pattern was analyzed, as shown in **Figure 5.** In the transverse and longitudinal ports of 4043 and 4047, the dimples produced by the two tensile parts have small differences in size, and the dimple morphology is basically similar. In addition, compared with the two different Al-Si alloys, it can be found that the dimple size of 4043 aluminum alloy is larger. This also confirms that 4043 aluminum alloy has lower strength.

There are four factors affecting the strength of metal materials, including the effect of solid solution, the effect of dispersing the second phase, the effect of plastic deformation and the effect of grain refinement. The effect of solid solution strengthening refers to the melting of alloy elements into the aluminum alloy matrix. Aluminum alloy is strengthened by the size effect, elastic effect and solid solution orderliness of solute atoms. Deformation strengthening refers to the aluminum alloy after cold deformation, dislocation density increases, entanglement occurs, and cellular structure is formed, which makes dislocation movement difficult, thus improving the strength and hardness. The second phase precipitates from the susaturated solid solution to form a coherent strain zone, which leads to the increase of the movement resistance of dislocation is called precipitation strengthening. The refinement of grain in microstructure can improve the strength and hardness of crystal. In addition to 4043 and 4047 aluminum alloy, there is no plastic deformation of the material, so there is invisible hardening. There is no dispersing strengthening phase of 4043 and 4047 aluminum alloy, and no second phase precipitates out of the two materials, so there is no precipitation strengthening. The only factors affecting the strength of Al-Si alloy are the strengthening of α-Al matrix and the strengthening of Al-Si eutectic and fine crystal. However, the proportion of the specific weight of the strengthening of fine crystal in the strength of alloy is smaller. Because the content of eutectic silicon in 4047 aluminum alloy is more than that in 4043 aluminum alloy, Moreover, the strengthening effect of Al-Si eutectic material is more advantageous than that of pure Al matrix, so the strength of 4047 Al alloy additive is higher, but the large amount of eutectic silicon makes the plasticity poor. Moreover, there is no directivity of these two intensifiers, and there is no unique directivity of grain shape on the whole, so Al-Si alloy materials do not have anisotropy problems.

4.Conclusion

In this paper, TIG arc additive tests on 4043 and 4047 aluminum alloys were completed, and the main conclusions were as follows:

1)The wall formed by 4043 aluminum alloy is better than 4047 aluminum alloy. The increase of silicon content makes the metal liquid in the melting process of 4047 welding wire have better fluidity, and it is easier to form a hump in the additive process.

2) The crystal structure of 4047 aluminum alloy is uniform in grain size and lattice type distribution, and α-Al mainly presents secondary dendrite structure, while the lattice type distribution of 4043 aluminum alloy is uneven. Most of the primary aluminum phase forms columnar crystals, but a small amount of grid crystals are also produced. This is mainly due to the rapid cooling of grain during pulse arc short circuit.

3) The average tensile strength of 4047 aluminum alloy additive is higher than that of 4043 aluminum alloy additive, but the plastic ratio is worse.

4) The strength of 4043 and 4047 aluminum alloy additions mainly comes from α-Al matrix strengthening and Al-Si solution strengthening, and the effect of grain boundary strengthening is small. There is no directivity of these two kinds of strengthening, and there is no unique directivity of grain shape on the whole, so Al Si alloy materials have no anisotropy problem.

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