The Microstructure and Mechanical Properties of 308L Alloy Fabricated by Micro-plasma Arc Additive Manufacturing

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Abstract. In this article, micro-plasma arc additive manufacturing of 308L alloy was conducted and the microstructures and mechanical properties of the fabricated specimens were investigated. Micro-plasma arc was adopted as heat source and forming paths were varied during wire and arc additive manufacturing (WAAM) by using ER308l wire. The results showed that the Z-type forming path specimen’s quality was better than the unidirectional forming path’s. Analysis of the microstructures and mechanical properties of the specimens showed that the Z-type forming path specimen had a higher tensile strength, hardness value and percentage of elongation than unidirectional forming path specimen. The Z-type forming path and the unidirectional forming path specimens’ microstructures were both composed of austenite and ferrite, but the Z-type forming path specimen’s microstructure had larger grain size and it showed a distinct crossed microstructure.

1. Introduction
Additive manufacturing technology emerged in the 1980s. Metal additive manufacturing technology can be classified according to the different heat sources adopted during the manufacturing process, such as laser, electron beam and electric arc [1]. Wire Arc Additive Manufacture (WAAM) is an advanced technology manufacturing materials layer by layer, which uses the arc generated by Metal Inertia Gas Welding (MIG), Tungsten Inert Gas Welding (TIG), and Plasma Arc Welding(FA) machine as heat source [2-3]. Through the feeding of wire or powder, it can use the three-dimensional digital model to construct metal parts from plane to solid. Compared with TIG Welding, micro-plasma arc welding has more concentrated energy beam, smaller heat affect zone and post welding distortion. And temperature of the Micro-plasma arc is 2.5 to 3 times higher than that of the Tungsten Inert Gas Welding, which can reach 16000°C [4]. Micro-plasma arc additive manufacturing uses micro-plasma arc arc as heat source through the feeding of wire or powder, and the current is less than 50A. According to calculated path, it could achieve the stacking of materials on the surface of the workpiece [5]. The advantages of laser and electron beam additive manufacturing technology are that they could prototype small and complex components rapidly. However, the arc additive manufacturing technology has its own advantage that it could prototype large and complex components rapidly with lower cost and high efficiency [6].

Stainless steel has good plasticity, toughness, weldability, chemical corrosion resistance, high temperature resistance and good mechanical properties [7]. Because of its good chemical corrosion resistance, it is commonly used to make corrosion resistant containers, equipment linings, conveying pipes and Nitric acid resisting parts, etc. Stainless steel could maintain its excellent physical and
mechanical properties at high temperature, and it is widely used in additive manufacturing. Stainless steel powder has good moldability, simple preparation process and low price. It is the one of the earliest materials used in metal additive manufacturing. At present, research on the additive manufacturing of stainless steel materials mostly uses stainless steel powder, and there are few researches on the additive manufacturing of stainless steel wire, especially for 308L stainless steel. For this reason, 308L wire with a diameter of 0.8mm was chosen for the research of micro-plasma arc additive manufacturing in this paper.

2. Experimental Methodology
Feeding wire composed by 308L stainless steel with a diameter of 0.8mm was chosen as experimental feeding wire, and 304 stainless steel was used as the substrate. The substrate dimension was 200mm×120mm×8mm. The chemical composition of the experimental feeding wire was listed in Table 1. The micro-plasma arc additive manufacturing system used in this study was shown in figure 1. As shown in figure 1, the system consisted of KUKA KR C4 control cabinet, Fronius KD7000 wire feeder, KUKA KR20-3 industrial robot, SAF PLASMAFIX 51 micro-plasma arc welding source.

| Composition | C  | Si  | Mn  | S  | P  | Cr | Ni  | Fe |
|-------------|----|-----|-----|----|----|----|-----|----|
| Content(%)  | 0.03 | 0.6 | 1.8 | 0.008 | 0.015 | 20 | 10 | Bal. |

The experiment parameters used a peak current of 48A, and the duty cycle of 50%, the base current of 24A, the wire feed speed of 9mm/s, and the traveling speed of 2mm/s, the distance of 3.5mm from the substrate to welding gun. According to the two different forming methods shown in figure 2, 308L stainless steel wire was used to carry out additive manufacturing to form a thin wall specimen. After forming the specimen, the metallographic section was taken perpendicular to the direction of the forming path, the metallographic section was prepared after sanding, polish and corrosion. The HGO HSH-200C plane measuring microscope was used to observe the cross-section’s shape of the component, and the Axio Imager M2m optical microscope was used to investigate the microstructure of the component after WAAM. The Buehler VH1202 Micro Vickers hardness tester was used to measure the hardness of the component. The tensile specimen was taken along the welding direction, as shown in Figure 2, and the GOPOINT GP-FS2000M electronic cupping machine was used to measure the tensile strength and percentage of elongation of the component.

![Figure 1](image1.png) **Figure 1** Micro-plasma arc additive manufacturing system

![Figure 2](image2.png) **Figure 2** Different forming paths and tensile specimen preparing method
Unidirectional forming path  Z-type forming path
3. Results and discussion

3.1. Forming shape of the component after WAAM

Figure 3 showed the specimens obtained by the unidirectional forming path and Z-type forming path. When the unidirectional forming path was applied, the arc would be extinguished and the welding torch would return to the initial arcing position to arc again after completing the previous layer. The same procedure would be repeated until the forming was completed. While the Z-type forming path was applied, the welding torch would directly raise without extinguishing the arc, and move directly in the opposite direction of the previous layer, and this procedure would also be repeated until the forming was completed. It could be observed from the figure 3 that when the unidirectional forming path was applied, as the specimen height increased, the heat accumulated and it resulted in that the specimen’s height at the end of each layer became lower than the initial position. And the droplets were transferred under the plasma arc pressure, it resulted in the droplets spatter. A large amount of spattered droplets flew to the sides of the weld bead, and a few amount of spattered droplets fell into the molten pool, causing the difference in height between end position and initial arcing position, as shown in figure 3 (a). The difference of height between the arcing extinguished position and initial arcing position would affect the stability of the arc. As the height of the stack increases, the difference became larger, and the stability of the arc became worse and worse, finally the arc extinguished. Although the Z-type forming path specimen also had height difference between the arcing extinguished position and initial arcing position, but its forming shape was significantly improved, as shown in figure 3 (b). The shape of the specimen formed by Z-type forming path was more fluid than the Unidirectional forming path’s.

![Figure 3. The specimens formed by different paths](image)

In the arc additive manufacturing process, the different forming paths would affect the heat transfer conditions. As shown in figure 4, the interpass temperature of the specimens of different forming paths were different, which would cause the differences of microstructures. It could be observed from figure 3 4 that there were no obvious fusion lines, and the width of initial forming layer was the narrowest. Because the substrate was not preheated, the initial forming layer had the best heat dissipation condition, it resulted in that the initial forming layer had less time to spread, and the subsequent layers’ width gradually increases until it become a stable value. When the same number of layers was formed, the specimen obtained by unidirectional forming path was higher than the specimen formed by Z-type forming path. When use unidirectional forming path to form a specimen, arcing, extinguishing arc and moving between the arcing extinguished section and initial arcing section had cost dozens of seconds, it increases the cooling time between layer and layer, the interpass temperature became lower, and the layer height of the forming specimen was higher. Comparing two different forming paths, the layers of the specimen formed by unidirectional forming path was neater with regular height, and the layers formed by Z-type forming path was crossed with unregular layer height.
3.2. The microstructure of the specimens

Figure 5 showed the microstructure of the specimens obtained by two different forming paths. It could be observed that the specimen obtained by two different forming paths were both consisted of austenite and ferrite.

Figure 5. The microstructures of different sections obtained by different forming paths

Figure 5 (a), (b), and (c) showed the bottom, middle, and top sections of the microstructures of the specimen obtained by unidirectional forming path respectively. It could be observed from the figure 5 (a), (b), and (c) that the grain sizes of bottom and middle sections were bigger than the top section, it was mainly consisted of columnar crystals. The crystal grains grew along the height direction of the specimen, and the grains near the fusion lines between layer and layer were larger than the grains in the middle section of a layer. It was because that the previous layer had a preheating effect on the subsequent
layer, and the subsequent layer would heat the previous layer. The interaction between the previous layer and the subsequent layer made the cooling time prolonged, which prolonged the time for grain growth. While forming the subsequent layer, the surface of the previous layer would be heated first, and the heating had a remelting effect on the surface of the previous layer, so the grains near the fusion line were larger than the grains in the middle section of a layer. The grain size of the top section was smaller than that of the bottom and middle sections, because the top section was only preheated by the previous layer, and the heating of subsequent layer was not received. Compared with the bottom and middle sections, the cooling time of the top section was much less. Equiaxed grain and columnar grains could also be found in the top section of the specimen.

Figure 5 (d), (e) and (f) showed the bottom, middle, and top sections of the microstructures of the specimen obtained by Z-type forming path respectively. It could be observed from the figure 5 (d), (e) and (f) that the direction of grain growth and grain sizes of the specimen obtained by Z-type forming path were similar to the specimen obtained by unidirectional forming path. The grain sizes of bottom and middle sections were coarser than the top section. The difference between the two specimens obtained by different forming paths were that the microstructures of the specimen obtained by Z-type path had obvious crossed microstructures and bigger grains in the center of the layer. When unidirectional forming path was used to form, the arc was extinguished at the end of the previous layer, then the arc would be restarted at the starting position of the subsequent layer. When using the Z-type forming path, the welding torch would directly raise without extinguishing the arc, and moved directly in the opposite direction of the previous layer. Therefore, compared with the unidirectional forming path methods, the Z-type forming path method reduced the cooling time between layer and layer, which resulted in that the microstructure of the specimen obtained by Z-type forming path was coarser.

3.3. The mechanical properties of the specimens

Figure 6 was the tensile test specimens of two forming paths. The tensile strength of the specimen of unidirectional forming path could reach 547.7MPa, and its percentage of elongation was 41.3%. The tensile strength of the specimen of Z-type forming path could reach 588.6MPa, and its percentage of elongation was 50.6%. Figure 7 showed the microhardness distribution curve along the height direction of the components. It could be observed that the specimens obtained by the two different forming paths all showed a tendency to decrease in hardness as the number of layers increased. This was because that the previous formed part would be heated while the subsequent layer was forming, which equals to a heat treatment. The lower layers would suffer more times of heating, and it became harder. The average hardness of the specimen of unidirectional forming path was 176.1 HV, and the average hardness of the specimen of Z-type forming path was 179.0 HV. The average hardness of the specimen of Z-type forming path was slightly higher.

![Tensile test specimens](image)

(a) unidirectional forming path    (b) Z-type forming path

**Figure 6.** Tensile test specimens
4. Conclusion
1. Compared with the unidirectional forming path, the shape of the specimen obtained by Z-type forming path was more fluid and better. When unidirectional welding path was used, the arcing extinguished section collapsed and the arc was unstable.
2. The microstructures of different sections of unidirectional forming path and Z-type forming path were consisted of austenite and ferrite. The microstructures of the bottom and middle sections of the specimens were similar, it was columnar crystal region. The specimen of Z-type forming path was obviously crossed and coarse compared with the unidirectional forming path.
3. The tensile strength, hardness and percentage of elongation of the Z-type forming path were higher than those of the unidirectional welding path.

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