# Processing and Properties of 316 Stainless Steel Nuclear Grade Experimental Component Made by Additive Manufacturing

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**Abstract:** The high precision with arc shape 316 stainless steel apron plate experiment component was fabricated by wire and arc additive manufacturing (WA-AM) technology and its phases, microstructure, mechanical properties at room temperature, and nondestructive detection were investigated. Results showed that there were two phases austenite as matrix and lath shape ferrite distributed in reticular form in the WA-AM 316 component. The mechanical properties from tensile tests exhibited good performance in both UST (580 MPa) and YS (333 MPa) values. Its comprehensive properties are comparable to wrought nuclear industry 316 and exceed the requirements for 316 stainless steels. The overall quality of WA-AM 316 apron plate product detected by nondestructive testing met the nuclear industry requirements of the evaluation standard.

## 1. Introduction

Additive manufacturing (AM) technology also known as "3D Printing" technique. The AM concept of "Today Design, Tomorrow's Products" has attracted wide attention from universities, research institutes, aerospace and other large enterprises. AM technology has been developed for nearly a century. It has exploited originally from a laminated forming technology based on bonding principle, gradually develop to the light curing forming technology with ultraviolet light as the heat source, and then to the rapid melt forming technology with arc, electron beam, laser and other high energy beam as heat source. Thus, the rapid manufacture of organic materials, inorganic nonmetallic materials and metal materials products has been realized.

In recent years, the development of metal additive manufacturing technology has developed rapidly, which has influenced on the schema of the traditional design and manufacture techniques. Compared with the traditional metal materials manufacturing technology such as casting and forging, additive manufacturing method does not have to produce molds in advance and does not have to remove a lot of material during the producing process. The final metal products just need simple post treatment or not, avoid a complex forging process. Additive manufacturing is both technologically advantageous and economically competitive such as distributed manufacturing in modular manner, customizability, impossible to manufacture geometries, manufacturing and repairing large and complicated metallic components [1-5] Additive manufacturing method only requires one device for producing any complex shape of parts with quick and accurate process, which real realizes a dream of "free manufacturing". Thus, this new manufacturing technique could help solve the problem about the forming technique of many complex structural parts, and reduce the processing steps greatly, thus finally shorten the processing cycle. The more complex structure of the product, the more significant advantages of the additive manufacturing technology compared with other traditional technology. As a result, structural optimization, material savings and energy savings can be achieved in production. In the nuclear industry, the advantages of additive manufacturing technique are reparative for the difficulties to be solved in the design and manufacture of the modern new nuclear power equipment. However, due to the security considerations of the nuclear power industry and the restrictions of relevant laws and regulations, there are still many scientific problems need to be solved to promote the application of new technologies in the nuclear power industry.

The present work carried out an exploratory research on the process and properties of nuclear grade 316 stainless steel structural apron plate component made by a wire and arc additive manufacturing (WA-AM) technique. The high precision design requirement for the apron plate component with arc structure is urgently needed to make up for the shortcomings of traditional manufacturing technology. Through this research work, it is expected that the advanced process could be applied to the design in the new nuclear reactors in the future, even in the exploratory design of the experimental parts.

## 2. Experimental Procedure

The WA-AM 316 apron plate with a feature geometric size of 900 mm × 260 mm × 480 mm was fabricated by wire and arc additive manufacturing process through Fronius CMT Advanced 4000 WA power source with VR5000 wire feeding system. The WA-AM started from the XOY plane and the depositing direction was OZ, the whole stratification was formed in small modular manner as shown in Fig. 1. The whole WA-AM process was conducted by the protection of argon with the purity was not less than 99.99% in volume fraction. The beginning condition for WA-AM work was depended on the oxygen content less than 0.1% in volume fraction measured by oxygen analyzer. Only when the oxygen content was qualified, the manufacturing work can be carried out to avoid oxidation.

Considered the arc structure of the apron plate, a 316 stainless steel plate with a geometric size of 1200 mm × 800 mm × 90 mm was employed as a flat substrate. The surface of the flat plate was grinded to exhibit metallic luster by 1000# SiC paper, then cleaned with liquid acetone and dried. The fresh surface for WA-AM waiting time was not more than 4 hours.

In order to obtain the requirement on the accuracy and surface roughness of the arc in the apron plate, the follow-up of machining and accurate measurement was adopted.

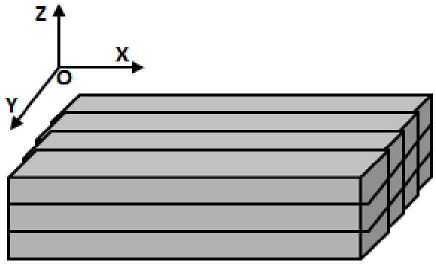


Figure 1 Schematic Illustration Direction Of WA-AM Process In Small Modular Manner.

After WA-AM process, the final product was experienced heat treatment at 1000~1100℃ and kept 2~3h, then cooling with furnace after wire and arc additive manufacturing.

Considered that this WA-AM 316 product was a nuclear grade experimental part, the quality should be controlled. According to China special standard, fluorescence detection (HB/Z 61) and ultrasonic testing (HB/Z 59) were employed to examine the surface state and the entity.

Mechanical properties were examined by tensile tests and Vickers hardness (HV) tests at room temperature. Round tensile specimens with 10 mm in diameter, 50 mm in gauge length and 114 mm in total length were prepared based on the China standard GB/T228 1-2010. The tensile specimens were sampled from three directions of OX, OY and OZ. Two tensile specimens were exploited for each group. The final experimental values were taken as the average values. For getting a hardness change on the metallographic specimens, Vickers hardness (HV) test was employed with loading 500g.

The 316 wire with a diameter of 1.2 mm was employed. The chemical composition of 316 stainless steel additive manufacturing product was measured and the result was given in Table 1.

Table 1 Chemical composition of WA-AM 316 product.

| Element | C | Cr | Ni | Mo | Mn |
|---|---|---|---|---|---|
| Content | 0.055 | 17.96 | 11.78 | 2.19 | 1.36 |
| Element | Si | S | P | Co | Fe |
| Content | 0.57 | 0.001 | 0.017 | 0.016 | Bal. |

The specimens were cut from the deposited component, and the two dimensions were XOZ plane. The preparation of the metallographic specimens by polishing and etched by a solution of 4 g $CuSO_4$, 20 ml HCl and 20 ml $H_2O$. Optical microscope (OM), scanning electron microscope (SEM) with back scattered electron imaging (BSE) and energy disperse spectroscopy (EDS) were used for the examination of the microstructure of WA-AM 316 product. X-ray diffraction (XRD) was used to identify the phases.

## 3. Results and Discussion

Fig. 2 shows the XRD phase analysis of WA-AM 316 specimen. The XRD examination result indicated that there were two phases in the WA-AM 316 product. The main phase was austenite (Fe0.7Cr0.19Ni0.11) and a little ferrite phase (NiCrFeIm3m).

The microstructure of the WA-AM 316 specimen is presented in Fig. 3a. Lots of coarse elongated austenitic grains were formed, and the reticular ferrite phases were distributed in the grain boundary. The analysis combined with SEM-BSE results (Fig. 3b) indicated that there were two phases microstructure obviously in the WA-AM 316 component. The matrix phase is austenite and the lath about 1 μm in width is ferrite. In addition, the spheroids distributed in the austenite matrix were analyzed by EDS, and the oxygen content had reached 18 at. %. There were two possible conclusions on the spheroids phases. One was that it was oxide inclusion formed during the WA-AM process. Another one was believed that some spherical holes were existed in the material matrix attributed to the manufacturing process since no other phases displayed in XRD detection.

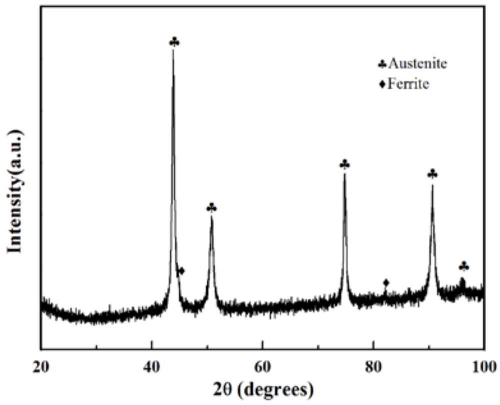


Figure 2 XRD Phase Analysis Of WA-AM 316 Product.

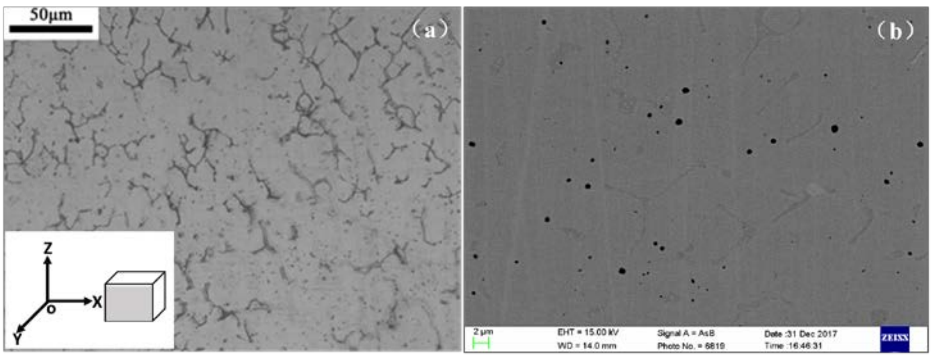


Figure 3 (a) Optical Microscope Photo and (b) SEM-BSE Photo Of WA-AM 316 Product.

Fig. 4 shows the Vickers hardness of WA-AM 316 specimen along the vertical in the direction of deposition with a distance of 0.5mm. The minimum hardness value is 177.6 HV, and the maximum one is 200.4 HV. The curve of Vickers hardness shows zigzag distribution, which indicates the existence of two phases (austenite and ferrite). The uneven shape is attributed to the change of the two phases in ratio and the disturbance from the spherical phases or holes.

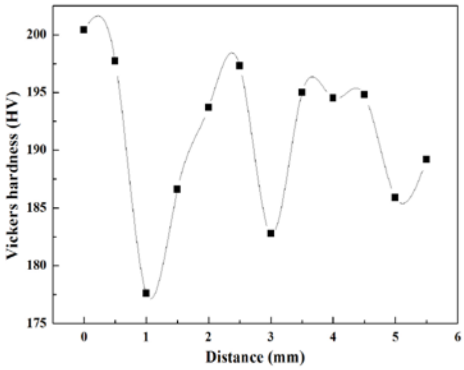


Figure 4 Vickers Hardness Distribution Of The WA-AM 316 Specimen.

The ultimate tensile strength (UTS) and yield strength (YS) are calculated from stress/strain curves of WA-AM 316 specimens and the results are given in Table 2 compared with the values from the nuclear industry and the requirement based on the ASME standard. The tensile properties of WA-AM 316 tested at room temperature, including ultimate tensile strength (UTS), yield strength (YS), elongation (EL) and reduction of area (RA) exceed the nuclear industry requirements for 316 stainless steels. Both the performances of UTS and YS from WA-AM 316 specimens are comparable to wrought nuclear industry 316, but the values of EL and RA are lower than the ones.

Table 2 Tensile properties of the WA-AM 316 product at room temperature.

| Tensile tests | UTS/MPa | YS/MPa | EL/% | RA/% |
|---|---|---|---|---|
| WA-AM 316 | 580±7 | 333±13 | 35±2 | 47±7 |
| Wrought 316 from nuclear industry | 569 | 276 | 56 | 79 |
| Wrought 316 from nuclear industry | 590 | 275 | 75 | 60 |
| Nuclear industry requirement for 316 | ≥485 | ≥205 | ≥30 | ≥45 |

In the product quality inspection, the final WA-AM 316 apron plate component was detected by fluorosmosis, no linear defects such as cracks and dense stomatal defect were found. Besides, after ultrasonic testing, WA-AM 316 apron plate component had not been found to exceed the standard defects, which met the nuclear industry requirements of the evaluation standard with no visible defects.

## 4. Conclusion

We have experimentally investigated the 316 stainless steel wire, and wire and arc additive manufacturing (WA-AM) process to make high precision with arc shape apron plate component. The final WA-AM 316 apron plate product was studied by phase examination, microstructure analysis, mechanical properties testing, and nondestructive detection.

The main conclusions are:

- The two phases were austenite as material matrix and lath shape ferrite;
- The mechanical properties from tensile tests exhibited good performance in both UST (580 MPa) and YS (333 MPa) values. Its comprehensive properties are comparable to wrought nuclear industry 316 and exceed the requirements for 316 stainless steels;
- The quality of WA-AM 316 apron plate product detected by nondestructive testing met the

nuclear industry requirements of the evaluation standard.

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