Current Research Situation and Prospect of Wire and Arc Additive Manufacturing of Titanium Alloy

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Abstract: Wire arc additive manufacturing is an important part of additive manufacturing. Because of its low processing cost, high forming efficiency, high material utilization rate and low equipment cost, it is favored in the fields of medical and aerospace. This paper briefly discuss the technologies of titanium alloy wire arc additive manufacturing. The influence of different deposited parameters, interpass rolling, ultrasonic assistance and heat treatment on the forming quality of titanium alloy wire arc additive components are summarized and analyzed. Finally, combined with the actual engineering requirements, the problems and research directions of the development of titanium alloy additive manufacturing are analyzed.

Keywords: Wire and Arc Additive Manufacturing; Titanium Alloys; Microstructure; Mechanical Properties; Research Progress

1. Introduction

Titanium alloy have excellent physical and mechanical performances, exempli gratia，the high specific strength, corrosion-resisting, biocompatibility, high creep with fatigue resistance. Therefore, it is widely utilized in the petroleum and energy industries, metallurgical industry, marine industry, automotive industry, aerospace and food, medical equipment and other fields [1].

Due to the small deformation coefficient, high cutting temperature and easy hardening of titanium alloy during processing, titanium alloy has poor machinability and is a typical difficult-to-cut material. Manufacturing titanium alloy structural parts by traditional forging and machining methods requires cutting off about 90% of the raw material. There are some disadvantages such as long cycle, low material utilization rate and poor economy.

Compared with traditional metal cutting, additive manufacturing can directly process near-net-shape parts, can improve the design flexibility, enhance the ability to manufacture complex parts, known as the "transformative" low-cost, short-cycle, high-performance, "shape control/control" integrated manufacturing technology for the manufacture of Like titanium alloy hard-to-machine metal parts to provide a new technology path[2].

Additive manufacturing technology originated in the 1980s, based on the discrete, stacking principle, according to the three-dimensional model design data using the material layer by layer method of stacking into a three-dimensional entity technology.

Compared with the reduction manufacturing technology such as turning, milling, planing, grinding and the manufacturing technology of casting, forging and so on, additive manufacturing is a "bottom-up" on the accumulation of material processing technology, and therefore not subject to the limitations of the size, volume and complexity of the part, can quickly and accurately complete the processing of complex structural parts. Additive manufacturing has many advantages, including high material utilization, no need for tools and molds, design flexibility and personalized manufacturing, in aerospace, medicine and other fields have been widely used, is now widely recognized as the key to achieve "Industry 4.0", is the production of high-performance parts of the mainstream technology.

Additive manufacturing is composed of two forms according to different raw materials，

Metal additive manufacturing and non-metal additive manufacturing, of which metal additive manufacturing is divided into electric arc, laser and electron beam due to the different heat sources, and materials for processing used are metal powder and metal welding wire two kinds. Among them, wire and arc additive manufacturing (WAAM) is a novel technique that has developed rapidly in the past 30 years. The process does not require molds and only a small amount of subsequent machining, which reduces the cost and improves the efficiency. It has become one of the economic and rapid forming methods that can realize high-quality titanium alloy structural parts.

This paper combed the domestic and international literature, introduced the definition, classification and characteristics of WAAM, systematically summarized the effects of process parameters, interpass rolling, ultrasound-assisted and heat treatment on the material microstructure and mechanical characteristic of titanium alloy WAAM, and looked forward to the future direction of development of titanium alloy WAAM.

2. WAAM Process

2.1 Definition of WAAM

WAAM is based on traditional welding technology. The metal wire is melted by arc or plasma arc, and is laid layer by layer on the base plate according to the set processing path to form a component. As figure 1. illustrates，a typical WAAM system mainly includes the following parts, for instance, the computer systems for control, an industrial robot, the wire feeding mechanism, welding machine and other equipment[3].

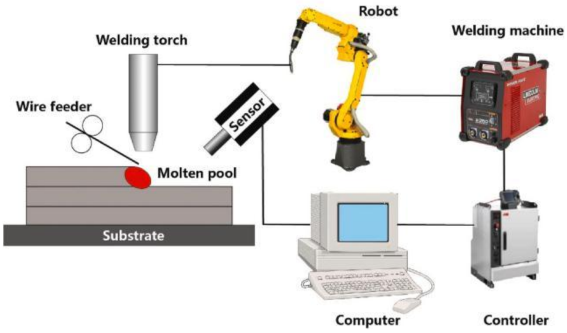
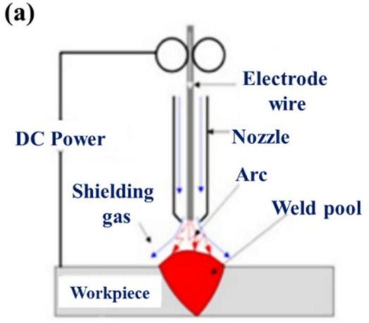


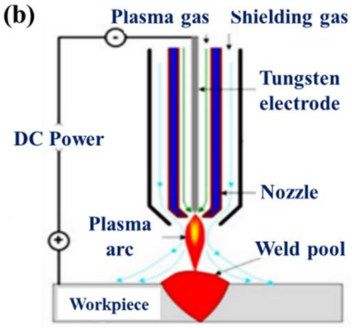
Figure 1. Typical WAAM System Composition [3]

2.2 Classification of WAAM

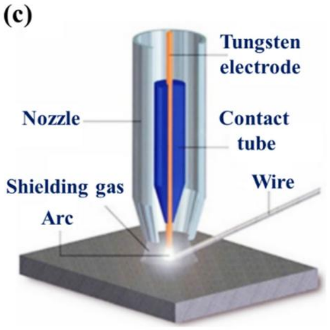
The deposition methods of arc additive manufacturing technology mainly include GMAW, GTAW and PAW. Figure 2 illustrates the working principle of the WAAM system based on the three energy sources[4].



(a) GMAW



(b) GTAW



(c) PAW

Figure 2. Schematic Diagram of Three Commonly Used Heat Sources in WAAM[4]

(1) GMAW

GMAW includes metal-inert gas welding (MIG), Metal active gas arc welding (MAG)and carbon-dioxide shield welding CO_2 gas shielded welding(CO_2 welding). In the process of metal welding, the high temperature heat is generated after the arc of the welding torch to melt the parts and the welding wire. In this process, the welding wire should not only act as the electrode to form the arc heat source, but also melt and fill the material to realize the connection of the parts. GMAW process uses continuous wire feeding and high current density, so the process has the advantages of simple structure, high productivity, and high deformation rate, but there are also the disadvantages of poor stability of the additive process, large heat input and low molding accuracy[5].

Cold metal transfer (CMT) is an AM technology developed on the basis of GMAW and short-circuit transfer. The metal welding wire is used as the melting electrode. In the process of arc generation, The welding control system automatically detects the arc state and automatically adjusts the current of the welding machine. When the arc is generated, the control system automatically reduces the current and extinguishes the arc.. The circuit is shorted, the welding wire is rapidly pumpback, the droplet separation is promoted, and the droplet is drop from the wire to complete the metal droplet transition. The technology has the preponderances of low heat input, stable processing and without droplet splash.

(2) GTAW

Tungsten argon arc welding (GTAW) uses inert gas as the shielding gas, and the heat generated by the arc between the tungsten electrode and the workpiece is used as the heat source to realize the welding process. The tungsten needle is used as the arc carrier, and there is no influence between wire feeding system and heat source system, so the welding process is free from oxidation and spattering, and the arc is stable with high weld strength.

(3) PAW

Plasma arc welding uses a high-energy plasma arc as a heat source to melt the material to achieve welding. During welding processing, arc heating dissociates the gas. When the gas pass through the water-cooled nozzle at high speed, the gas is condensed so that the concentration of energy and degree of dissociation are improved, and finally the plasma arc is formed. The stabilization, heating value and temperature of the plasma arc welding are higher than those of the general arc, and the arc energy can reach 3 times of the GTAW welding. Therefore, it has larger penetration force and welding speed, and has the superiorities of energy focus, high production rate, fast welding speed, small deformation and Good arc stability[6].

2.3 Characteristics of WAAM

The arc additive manufacturing technology forms a large melt pool with fast forming speed and small subsequent cutting. In terms of processing equipment, it does not require a special forming environment, small investment in equipment, and is easy to realize digital, intelligent and flexible manufacturing; the size of the equipment has no effect on the size of the parts, and it can manufacture parts close to the net, which is suitable for the processing of large-size and complex shape components. In terms of materials, arc additive manufacturing uses metal wires, which are easier to prepare and less costly than metal powders. Compared with traditional subtractive manufacturing, it has a higher material utilization rate. Compared with the laser powder process, the cost of parts produced by WAAM process is much lower. WAAM formed parts consist of full welded metal with uniform organization, which has advantages of good metallurgical bonding properties and high densities[7].

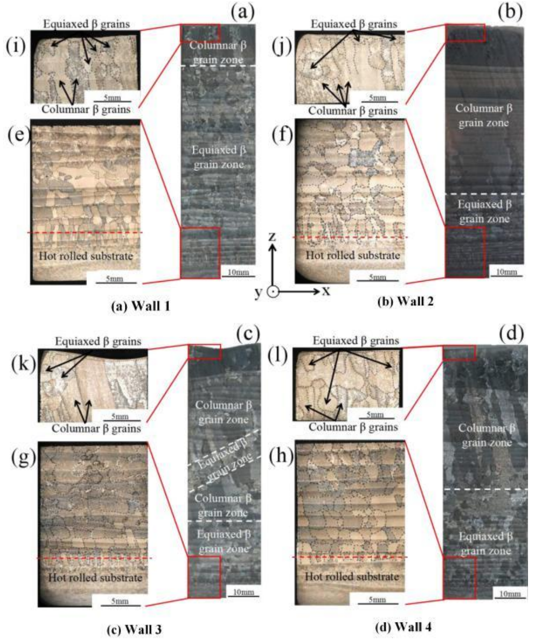
3.Methods to Improve the Quality of WAAM Components

WAAM is not perfect, and there are many disadvantages. The heat input is large, and it constantly undergoes the thermal cycling process of heating-condensing-heating several times, and the excessive heat input produces serious heat accumulation, which leads to poor precision and coarse grains in titanium alloy parts. The high temperature gradient leads to the epitaxial growth of β grains with columnar morphology, causing serious anisotropy and reduce the mechanical properties. Domestic and foreign scholars have tried a variety of methods to improve the surface roughness and process property of arc additive workpieces, which are reviewed from four aspects: process parameter optimization, rolling, ultrasonic assisted and heat treatment.

3.1 Deposited Parameters

The WAAM deposited parameters mainly include welding current, welding voltage, wire feed rate, heat input, welding speed, and interlayer temperature, which are one of the most important factors in WAAM forming. During processing, reasonable selection of process parameters is beneficial to obtain stacked metals with good forming quality and few internal defects, to achieve grain morphology control and to improve mechanical properties[8].

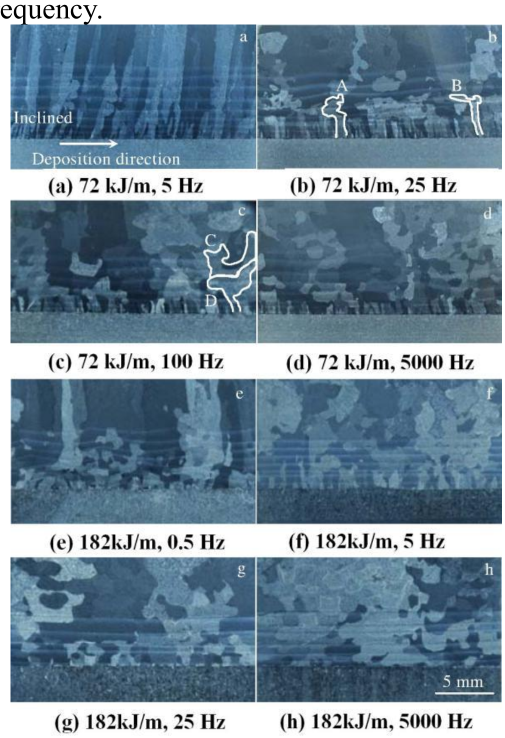
Wang et al.[9] researched the influence of welding current, welding speed, and wire feeding speed on the evolution of grain morphology and weave characterization in the build-up direction for Ti-6Al-4V alloy manufactured by WAAM. As shown in figure 3, with the increase of welding current and the decrease of wire feeding speed and welding speed, the average equiaxed β grain size increases. This indicates that high temperature is favorable to grain growth, and high rate of cooling is favorable to the shortening of grain growth time.



(e)-(h) Enlarged image of inset at the bottom of wall respectively showing the equiaxed β grains.
(i)-(l) Enlarged image of inset at the top of wall respectively showing the mixed macrostructure of equiaxed and columnar β grains.

Figure 3. Cross Sectional Grain Morphology of the Inner Walls (X-Z Section) [9]

Ma et al. [10] researched the influence of heat input and pulse frequency on the organization of Ti-6Al-4V alloy manufactured by WAAM. As shown in figure 4, increasing the pulse frequency can transform β-pillar crystals into equiaxed crystals to achieve grain refinement. Reducing the temperature gradient can also be achieved by increasing the heat input, which is beneficial to the formation of equiaxed crystals. This is because with the increase of arc pressure and electromagnetic force, the flow rate of liquid metal becomes faster, the dendrites are broken and the temperature gradient can be reduced. The decrease of heat input leads to the gradual increase of cooling rate and the refinement of α phase. However, the morphology of α phase does not change significantly with the change of pulse frequency.



(a) 72 kJ/m, 5 Hz (b) 72 kJ/m, 25 Hz
(c) 72 kJ/m, 100 Hz (d) 72 kJ/m, 5000 Hz
(e) 182kJ/m, 0.5 Hz (f) 182kJ/m, 5 Hz
(g) 182kJ/m, 25 Hz (h) 182kJ/m, 5000 Hz

Figure 4. β Grain Morphologies of Walls Deposited with Different Parameters [10]

3.2 Interpass Rolling

Interpass rolling can produce a certain plastic deformation through mechanical force and form a certain reinforcement layer, which can not only effectively refine the grain and reduce the porosity and other weaving defects, but also effectively reduce the anisotropy and residual stresses in the titanium alloy additive components [11].

Martina and Colegrove et al.[12-14] investigated the organization and property changes of Ti-6Al-4V alloy manufactured by WAAM before and after different rolling pressures. The cold rolling mechanism as shown in the figure 5 and 6 was used for stepwise rolling on the formed weld channel. The results showed that the β crystal refining effect became more and more obvious with the rise of rolling load, and the minimum could reach 89μm, and the thickness of the lamellar α phase was reduced to 0.62 μm. As shown in the figure 7, the average grain size was significantly reduced after rolling at a pressure of 75 k N. The tensile strength was increased in all directions to 0.5μm, and the thickness of the α phase decreased to 0.5 μm, which was the same as that of the α phase. The tensile strength in all directions is increased to about 1080 MPa, and the mechanical properties exceed those of forgings.

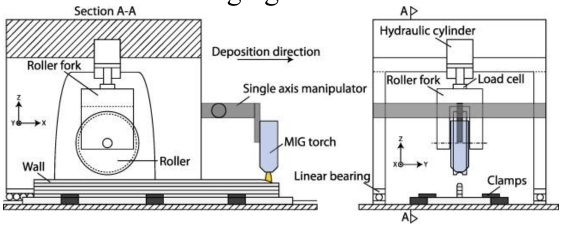


Figure 5. Schematic Diagram of Rolling and Welding Equipment [13]

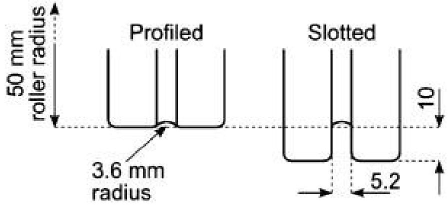
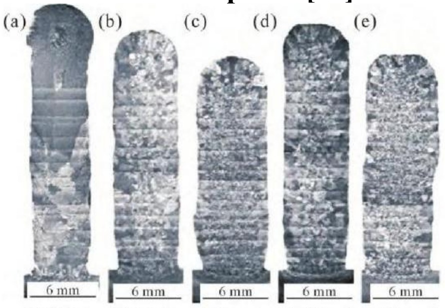


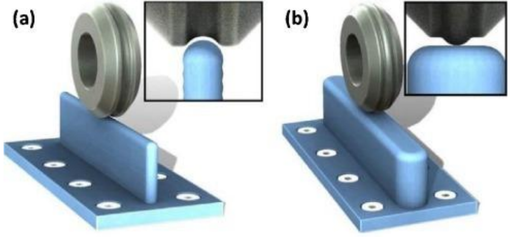
Figure 6. Roller Designs Applied to the WAAM Deposits [12]



(a) without interlayer rolling (b) round roll rolling (50 kN) (c) round roll rolling (75 kN) (d) flat roll rolling (50kN) (e) flat roll rolling (75kN)

Figure 7. Metallograph of Ti-6Al-4V Alloy under Different Rolling Parameters [14]

McAndrew et al.[15] developed a new "inverted profile" roll as shown in the figure 8, the degree of grain refinement has a great relationship with the size of the roll, a larger roll radius can increase the scope of recrystallization, so that more equiaxial crystals generated. The results show that the finest grains are produced by a rounded convex roll with a radius of 3 mm, as shown in Figure 9.



(a) vertical with a profiled roller (b) rolling with an inverted profiled roller

Figure 8. Schematic Diagram of the Rolling Methods[15]

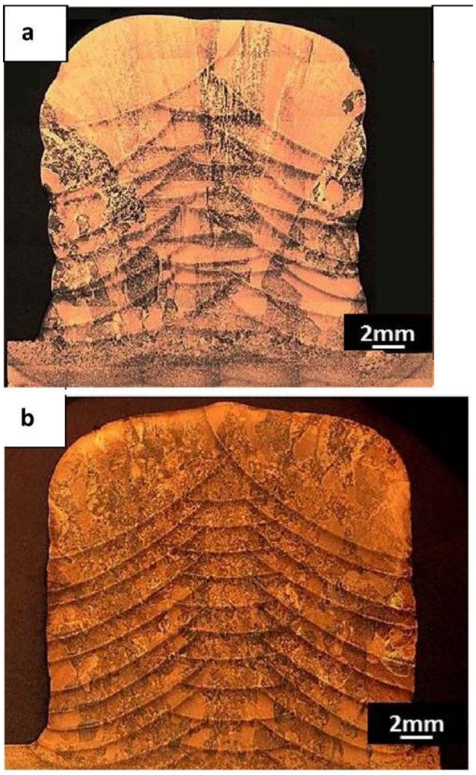


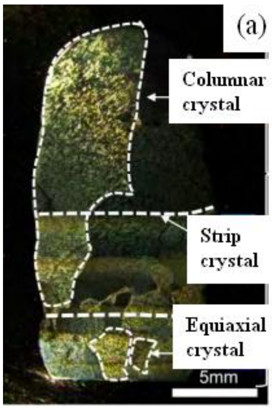
Figure 9. The Microstructures of the Unrolled Sample and a Rolled Sample [15]

3.3 Ultrasound-Assisted

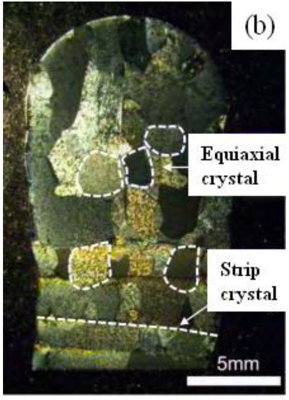
Conventional ultrasound-assisted methods have proved to be favorable to reduce the residual stress generated by welding in welding, effective techniques for reducing residual stresses in welded structures and improving fatigue properties.

He et al.[16] combined ultrasonic impact and WAAM. Figure 10 shows that under the action of ultrasonic impact, the coarse columnar crystals in the titanium alloy deposition layer are transformed into fine equiaxed crystals. At the same time, the percentage of tensile strength anisotropy was reduced from 12.5% to 1.5%.

Xu et al.[17] found that after the assistance of ultrasonic impact, the size of coarse β-columnar crystals in the bonding zone was significantly reduced, which led to grain refinement and more equiaxial crystals, and the best effect was achieved when the ultrasonic power was 600 W, as shown in Figure 11. After adding ultrasonic assistance, the tensile strength is improved in both horizontal and vertical directions. The results show that the addition of ultrasonic assistance can effectively improve the mechanical properties of the parts.

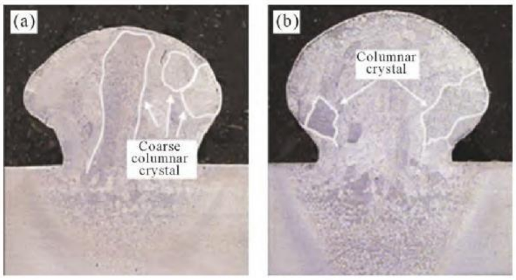


(a) without ultrasonic impact

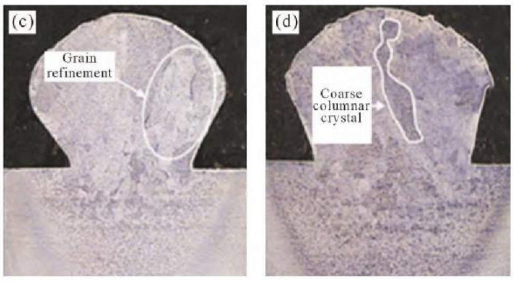


(b) with ultrasonic impact

Figure 10. Comparison of Macroscopic Organization and Morphology[16]



(a) without ultrasonic impact (b) 200 W ultrasonic impact



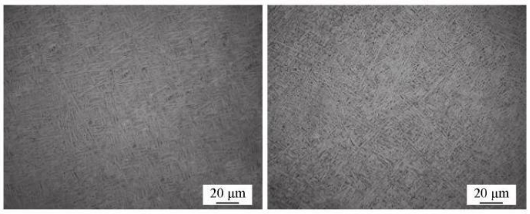
(c) 600 W ultrasonic impact (d) 1600 W ultrasonic impact

Figure 11. The Single Cross Section Macroscopic Morphology of Ti-6Al- 4V Alloy under Different Ultrasonic Impact Parameters[17]

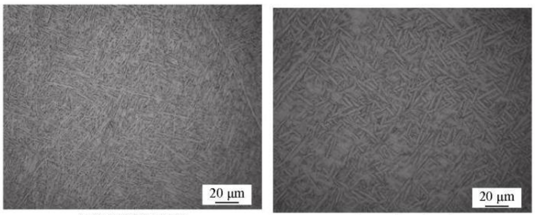
3.4 Heat Treatment

Due to the near-net shape characteristics of the AM process, heat treatment is one of the important ways to eliminate stress, stabilize microstructure in WAAM[18].

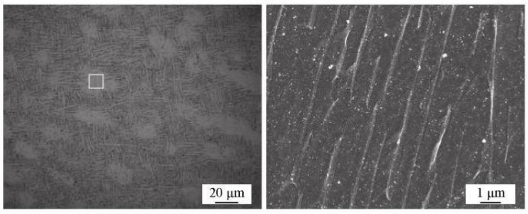
Xu et al.[19] carried out different normalizing treatments on TC4 titanium alloy prepared by WAAM. As shown in Figure 12, when the deposited layer was normalized in the range of 750 ~ 950 ℃, the α-phase organization became shorter and coarser with the increase of temperature, and transformed to the direction of basket-like organization. When normalized in the range of 950 ~ 1.050 °C, with the increase of temperature, the microstructure changes from basket-weave structure to α + β structure, and the needle-like primary α phase structure is refined. Compared with the normalizing treatment at 750 ~ 950 °C, the normalizing treatment at 950 ~ 1050 °C resulted in a finer acicular primary α-phase. After normalizing treatment, the mechanical properties of the samples in y and z directions increase first and then decrease, and the best mechanical properties were reached at 850 ℃/2 h/air-cooling.



(a) As-deposited (b) 750 ℃/2 h/ AC



(c) 850 ℃/2 h/ AC (d) 950 ℃/2 h/ AC



(e) 1 050 ℃/2 h/ AC (f) SEM morphology of the rectangular region

Figure 12. Microstructure of Specimen in Different States [19]

Bermingham et al.[20] investigated the influence of heat treatment process on the organizational properties of Ti-6Al-4V alloy manufactured by WAAM, and found that stress-relief annealing can significantly improve the plasticity while avoiding the organization coarsening. Hot isostatic pressing can reduce the microscopic defects, but it has little influence in the mechanical performance; and solid solution aging can improve the tensile strength, but the plasticity will be significantly reduced**.**

Gou et al.[21] analyzed the microstructure and mechanical properties of Ti-6Al-4V components prepared by WAAM with as-deposited and two different heat treatment methods were analyzed. After heating to 900 degrees constant temperature for 4 hours with furnace cooling and heating to 1200 degrees constant temperature for 2 hours with furnace cooling two different heat treatment methods, all α' martensites are transformed into α + β phase. The hardness and elongation of the parts after heat treatment have been greatly improved, but the tensile strength is significantly lower than that of the deposited parts.

Lexuri et al. [22] analyzed the effect of three heat treatment regimes on the mechanical performance of Ti-6Al-4V parts of different thicknesses prepared by WAAM. Three different heat treatments, 710°C for 4 hours, 850°C and 920°C for 5 hours, were used for post-treatment, and the values obtained as a result of the tensile tests were compared with those required by casting and forging method. As the heat treatment temperature increased, the elongation continued to increase and the strength decreases. With the exception of the 710◦ C treatment, anisotropy is also evident. In the horizontal direction strength is higher while elongation is low.

4.Conclusions and Future Research Directions

At present, WAAM has carried out many research on manufacturing process parameters, interpass rolling, ultrasonic assisted and heat treatment, and achieved many research results. However, the existing auxiliary regulation means still have their own limitations, and there are problems such as low precision of formed parts, non-dense organization, and anisotropy. For the purpose of realizing the wide application of titanium alloy WAAM technology in various fields, the follow-up work can be further carried out from the following three aspects:

(1) Composite additive manufacturing technology. Integrate the additive manufacturing technology with the traditional subtractive processing technology to develop a new additive and subtractive composite manufacturing system to achieve complementary advantages, and realize the integrated forming manufacturing of high-precision, high-quality complex structural components.

(2) On-line monitoring and dynamic regulation of the additive process. In the future, intelligent online monitoring and feedback control system should be further developed. In the process of machining, the process parameters are adjusted in real time according to the feedback of forming feature size, so as to realize the management of the whole process of WAAM titanium alloy component manufacturing, and ensure the internal quality and forming accuracy of the product.

(3) Integrate with with artificial intelligence, machine learning and advanced other technologies. Develop intelligent additive manufacturing equipment and design a multifunctional flexible and highly composite arc additive manufacturing platform.

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