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The process and mechanical properties of GH4169 columnar crystals fabricated by wire arc additive manufacturing

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Abstract. Wire- Arc Additive manufacture (WAAM) has been widely applied in metal field to control metal structure and microstructure. GH4169 is well fit to the WAAM due to its excellent weldability. While the columnar crystal has greater growth advantage than equiaxed crystal, so the superalloy GH4169 whose grain boundary induce its high temperature mechanical property will have fewer boundaries that can increase the property. While the shape of AM sample can be controlled, growth direction of columnar crystal can be adjusted through the heating method. If t growth directions of columnar crystals are consistent, the number of grain boundaries well induce largely. We can use different heating method and compare the result of growth direction. While the temperature environment at the top which decides the growth direction fit the requestion of growth direction, we can get the columnar that grows as we design.

Keywords: wire arc additive manufacturing, Nickel, Columnar crystal, Microstructure.

1. Introduction

The nickel base superalloy is an important kind of metal that is widely applied in aerospace field, such as the turbine blade of aeroengine. But the mechanical property of nickel base superalloy is more and more difficult to fit the elevated temperature environment where the temperature is increasing while the work environment is more hostile. So the grain boundary that improve the mechanical property at low temperature become the weak phase that induce the mechanical property at elevated temperature. Removing the grain boundary is the best way to improve the high temperature mechanical property.

The traditional manufacturing method is creating the directional solidification temperature environment with the help of mould that can remove the grain boundary enhancing the mechanical property at elevated temperature. But the cost is high and efficiency is low. Additive manufacture provides a new way to obtain the single crystal.

There are two kinds of additive manufacture whose materials are respectively power and wire. Compared to the former, the latter have more advantage that the product has less flaws decided by the stability of material transporting that can greatly reduce the mechanical property. The wire-arc additive manufacture (WAAM) is one kind of wire feeding additive manufacture, using the thermal energy provided by electric arc to melt the metal wire onto a substrate to build up a sample layer by layer. WAAM has a higher deposition efficiency than powder-based methods, so it has an advantage in building the large one. Due to the characteristic of near-net shape, WAAM consume less material[1], too.

WAAM has been applied in all kinds of metal manufacture, such as titanium alloy, magnesium alloy, etc. Heat input can be induced though the method of pulse current while the mechanical property and microstructure of Ti-6Al-4V change rarely[2] while the pulse frequency of WAAM will also change the grain size, grain shape, as well as the tensile properties[3]. And WAAM can maintain the stability of the shape and dendrites of the 304 L[4]. The microstructure of titanium also can be influenced by WAAM. The method of hot-wire obtained more equiaxed grains[5]. The pulse current of WAAM is able to influence the grain refinement of magnesium alloy AZ31,too[6]. So WAAM is an effective method that adjusts or controls the microstructure of metal.

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At present, metal structures additive manufactures including Selective laser melting (SLM) and laser melting deposition (LMD) have different characters. The layer of SLM is thinner than others and the precision of sample is higher, so it is widely used in the structure component which is complex and high requirements for density. The laser energy of LMD is high and the layer of sample is thick, so the efficiency of LMD is high. It is used for large size structure component. While WAAM has lower energy consuming, it can also achieve the manufacture of large size structure component. The method manufacturing single crystal need the high temperature gradient while the solidification velocity is consistent, or it will promote the forming of equiaxed grain. The WAAM can also provide the high temperature gradient environment. So WAAM is a ideal method manufacturing nickel base superalloy which can induce the cost, too.

Several kinds of nickel base superalloy, such as Inconel 625, Inconel 718 and Inconel 738 can be manufacture by AM to get the organization without interstices[7-12]. GH4169 is well fit to the metal-inert-gas (MIG) and tungsten-inert-gas (TIG) due to its excellent weldability[13, 14]. At present GH4169 alloy has been extensively studied in all kinds of additive manufacture. The gradient structure of GH4169 and K418 alloys manufactured by laser metal deposition has a lower mechanical property than the cast, but a better elongation. Other kinds of additive manufacture sample have different microstructure and mechanical properties. Scanning Laser Epitaxy has been used in turbine engine hot-section component repair[15]. The WAAM manufactured GH4169 sample, having a different with the cast that consist of equiaxed grain, encourages the growth of columnar grain. While the growth direction is also influenced by the molten pool which is roving[16-19]. The GH4169 superalloy manufacturing, applied in all kinds of elevated temperature environment, should reduce the number of grain boundary which reduce the mechanical property in high temperature. The character of building layer by layer creates a directional temperature gradient environment conductive to the growth of single crystal which is also benefited from the remelting[20]. WAAM is able to control the process parament to maintain a favorable environment that encourage the growth of columnar crystal.

Laser surface re-melting of directional solidified can achieve the epitaxial growth behavior that the epitaxial dendrites have the same orientation with that of the substrate[21]. The temperature gradient and crystal growth velocity take an important part. It mean that columnar crystals whose growth direction is consistent can be obtained from the coarse dendritic substrate, although equiaxed grains will appear at the top of re-melted layer. There are also same stray grains appearing around the carbides and eutectic phases. The element segregation causing carbides is the most important reason which can be solved by reducing heat input. Solute piling up in front of the solid-liquid interface may induce the constitutional undercooling ahead of the solid-liquid interface and then there will be homogenous nucleation occurring. While re-melting is a useful way to promote the epitaxial growth, continuous intense cooling condition can also facilitate it and the fewer stray grains can form. The misorientation of low angle boundaries will also be reduced with the help of intense cooling.

We can know that the epitaxial growth can appear in metal additive manufacture, while temperature gradient, crystal growth velocity, and the temperature of substrate have a great influence in crystal growth. And this effect can be controlled by the process parameter of WAAM. So WAAM can also be used to induce grain boundaries while it consumes less material. The columnar structure is obviously anisotropic, and has different mechanical property in different direction. The paper mainly studies the columnar crystal growth direction that can be changed by WAAM, the microstructure and the mechanical property parallel to the building direction.

2. Experiment

The material that this experiment used is the commercial GH4169 wire with 1.6 mm(Table 1).

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Table 1. Chemical composition of GH4169 wire (wt%)

Element	C	Cr	Ni	Co	Mo	Al	Ti	Fe
Composition (%)	≤0.08	17.0-21.0	50.0-55.0	≤1.0	2.80-3.30	0.30-0.70	0.75-1.15	balanced

The WAAM equipment is consist of control unit, welding unit, feeding unit, scanning unit and argon shield unit. The control system is connect with other units and sends various commands that decide behaviors of others, including feeding wire, arcing, quenching of arc and the movement of welding torch. The welding unit is the gas tungsten arc welding equipment which is used to melt the material. The location of molten material is controlled by scanning unit. The WAAM equipment (Fig.1a) manufactures the objective sample (Fig.1b) with the argon shield which protects the sample from being oxidized. The location of tungsten electrode is controlled by a three axis CNC system.

A WAAM columnar sample was built on a pure nickel substrate while the molten material dripped on the solidified metal after the substrate was heated. The process parameter was based on the phenomenon that the metal was just molten by the arc and the molten metal was not flowing optionally. Then we selected one set of parameter which caused sample having relatively smooth surface that mean the temperature gradient was easy to observe. The distance from the torch to the deposition surface was the variate that we study in this paper. No macroscopical defects appeared on the surface of sample. Metallographic and tensile specimens were processed as shown in Fig.1c and Fig.1d.

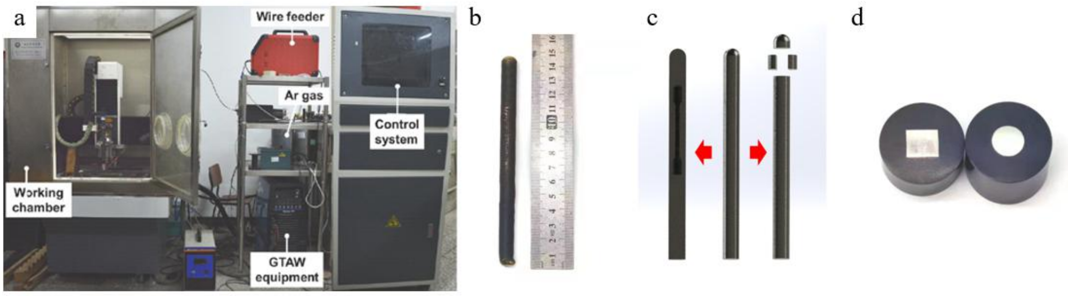

Figure 1. (a) WAAM equipment (b)sample (c)preparation method (the part showing the microstructure is at the top of the sample while the part used to test the mechanical property is at the center); (d)processed sample (including inlaying, grounding, polishing and etching)

The process parameters are shown in Table 2. The sample manufactured measures approximately 12mm in diameter and 150mm in height (Fig. 1b). The microstructure of the top of the sample was characterized and the middle part was for mechanical properties. The heat treatments were performed using a furnace. The process is homogenisation treatment at 1030℃ for 1h, air cool, and a standard double aging treatment (720℃ for 8h, furnace cool, and 620℃ for 8h, air cool). The dissected sample was dealt with a series of operations, including inlaying, grind and polish. Then the microstructure will appear with the help of corrosive liquid consisting of 10ml HCl, 10ml CH_3CH_2OH and 1g $CuCl_2$. The Electron Back-Scattered Diffraction (EBSD) sample will be processed by the professional way.

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Table 2: WAAM process parameters

parameters	Average current (A)	laye (mm)	Wire speed (cm/min)	Airstream (L/min)
value	21.5	0.30	10.5	20

3. Result and Discussion

3.1 Experiment result

The sample that WAAM manufactured was columnar as we can see while the height is 150mm and the diameter is 10-12 mm, and was heap up by layers whose thickness is more than 1 mm what we can see at surface. While the diameter of the sample at the bottom is 12 mm, thinner than that at the top which is about 10 mm, the growth direction at the bottom is less steady than that at the top.

The heat transfer rate of molten GH4169 is about 30 which is lower than most kinds of metal. It will be more different to solidify when it is molten, so the molten pool is thicker and the stability of the molten pool is more difficult to maintain. The molten metal can slip from the molten pool to the external which led that every layer we see at surface is much thicker than what we design on the control while the center layer has not changed. The slipped metal might change the temperature at surface and influence the temperature gradient. And at the beginning, the heat of molten pool transfer to the substrate, so the diameter is smaller when molten metal solidify more quickly. On the contrary, the sample is higher, the heat transmission rate through the built structure is lower, and the molten metal solidify more slowly which cause the thicker diameter.

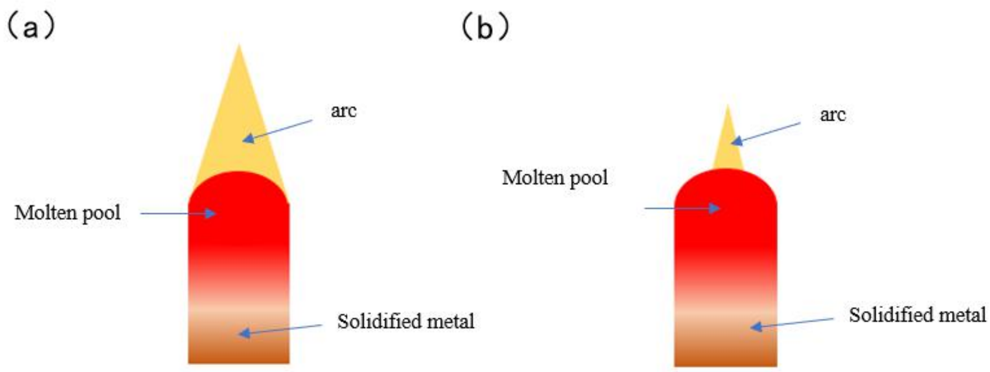

Figure 2. Two heating methods (a) The covering heating that the arc cover the top of the molten pool; (b) The center heating that the arc only cover the center part of molten pool

Two kinds of heat ways were adopted in this experiment (Fig.2). At different experiences, we found that microstructures were always different while heat input parameters are consistent. The only effect that can influence the heat input is the distance from the torch to the molten. When the distance is further, the voltage will be higher. So the heat input will change even though process parameters don't change. The temperature gradient may be influenced while the different areas are heated or not. So the growth direction may be different.

And surface characters are different. The sample covering heated had rougher surface. The layers shown at the surface were thicker. Because the nickel base superalloy is difficult to solidify and the external liquid metal was still being heated, so some of them would frow from the molten pool, so the surface would be rough. The sample center heated had more smooth surface while the heat input was less, and the surround liquid metal was not being heated, so it would solidify before flowing from the molten pool.

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3.2 Growth direction of columnar crystal

The arc can cover all molten pools in the covering heating, and only the center area was been heated in the center heating.

We can see the alternating light and dark bands at the bottom of Fig.4a which is not the result deposited GH4169 was etched abortively. They are the zones that material deposited was re-heated[22]. But the columnar crystals growth from the inter-layer and did not change the growth direction, so the columnar crystal can achieve the epitaxial growth.

At the first one, the top of the pool was absolutely hotter than the below, so the holistic heat flow is parallel to the building direction. The growth direction of the columnar crystal is also parallel to the building direction. As shown in the Fig.3, at the surrounding of the sample, the columnar crystal was growing as we think that the columnar grew from the bellow to the top while there is a little dig. So we can know that at the surrounding of the sample, the temperature close to the inside is lower on the same plane. The result is what we want to get. The stray grains would be weeded out while the columnar crystal growth.

But the growth direction of the center area changed a lot. The change of heat flow direction is the reason that caused this influence. According to the principle that the columnar crystal grows from the low temperature to the high temperature, we can know that the center of the sample had a higher temperature than that of others area which was caused by the heat accumulation on the same plane.

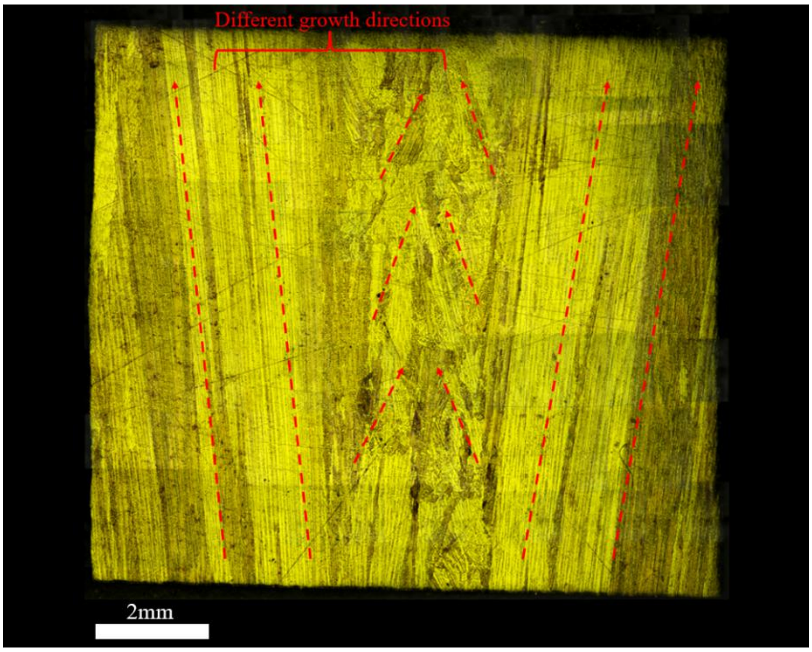

Figure 3. The growth direction of the covering heating columnar crystal

There are three reasons that caused the result.

The heat input is too high. The heat accumulation will be more while the heat input becomes more high and the cooling efficiency remains same if the value of temperature gradient almost do not change a lot at high temperature. So temperature at the center will reach high until the cooling efficiency influenced by the temperature gradient is equal to the efficiency of the heat accumulation.

The covering heating cause that the difference of the top of the sample temperature is little, so the heat transfer rate in the horizontal direction is also low which will also cause the heat accumulation of center.

The throughput of raw materials per unit time is too large. To maintain the balance of the layer and heat input, the wire feeding rate should increase accordingly. Therefore, the molten pool

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becomes thicker. The cooling efficiency in the building direction will decrease. And the heat in the molten is more that mean the heat accumulation will be more, too.

There are different temperatures at the top of molten pool, so the temperature gradient will change which influence the growth direction of columnar crystal. And growth directions of columnar crystals were random at the center. This is because the distance from torch to the molten was far and the stability of feeding wire was not certain, so the temperature entertainment at a small scale was not stable.

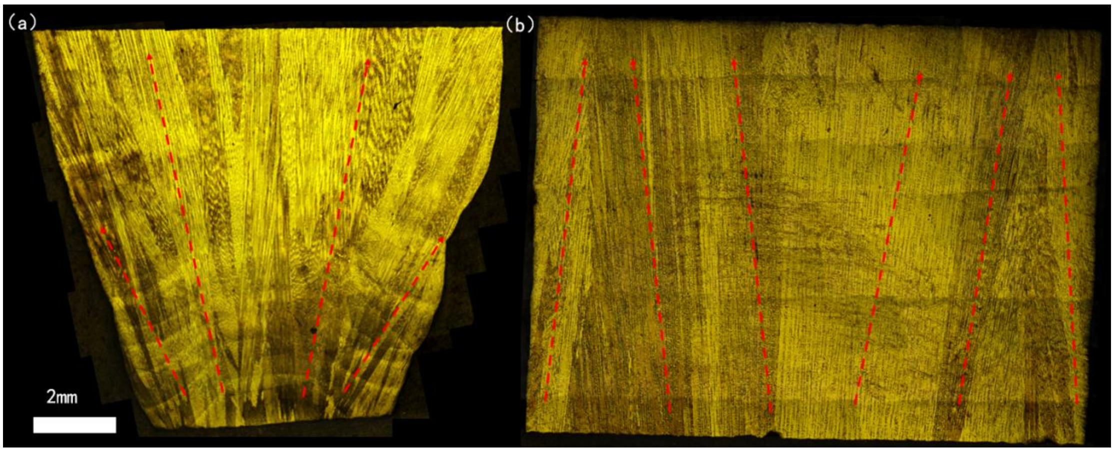

Figure 4. Center heating's growth direction of columnar crystal (a) the metal just grew from the substrate (b) the growth direction of columnar crystal maintaining stable

Center heating (Fig.2b) can change the growth direction of the columnar crystal (Fig.4) a lot as we can see. And the result is contrary to the covering heating. At the beginning, columnar crystals grew from center to the external area, which can weed out some external columnar crystal or equiaxed grain while the center crystal occupied the corresponding space. The direction of crystal growing is the most important factor. It is decided by the initial morphology of molten pool. The liquid metal was elliptic where the height of center is more higher, so the center columnar crystals grew to the external area where the external columnar should have grown. The temperature gradient at the center is much bigger than that at the external area while the substrate temperature is low at the beginning of additive manufacture. So the crystal at the center was more likely growing into columnar crystals while more equiaxed crystals were forming at the external area which was more easily to be weeded out.

When the molten pool got to the stable temperature, there were few columnar crystals grew to the external, and columnar crystals grew from the external to center. The arc of center heating was shorter than that of covering heating, so it had less heat input, so the heat accumulation became less, too. And there was lower temperature at the external area that was not been covered by electric arc than that covered by arc, which indirectly increased the heating efficiency. Then the heat flow and columnar crystals growth direction changed. The growth directions of columnar crystals were consistent at the center that is covered by the arc except the external. On the contrary, the new problem appeared at the external area comparing the covering heating. The lower temperature at the external caused by the less heat input changed the temperature distribution which decided the growth direction. But the columnar still grew from the low temperature to the high temperature, so the growth direction became opposite.

So the temperature distribution at the top molten pool decided the growth direction of columnar crystal. And the most important factors that decide the temperature distribution are heat input and heating method. So it is possible to get consistent growth direction when the temperature gradient is consistent.

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3.3 Grain boundary

The microstructure manufactured (Fig.5) by the center heating is divided into two area. There are few jumbo size grain boundaries at 50 x microscope, which is consistent to what we analyzed before. Some short grain boundaries can be seen at 100x microscope that the characters are different at different area.

At the center, there are fewer numbers boundaries that present a semi-enclosed structure. The dip angle which is the angle difference between growth direction of columnar crystal and building direction of the external is less than that of the internal that cause this structure while the direction of them were both growing from internal to the external. When the external dip angle is bigger, it will not influence the growth direction of the internal. There is enough space for internal columnar crystal to grow. And there were a few phenomenons that the external dip angle was little than the internal at the center. So the space for internal columnar crystals was occupied by external columnar crystals.So we can see the semi-enclosed structure.

At the external, grain boundaries distributed in disorder, and the area breadth was about 1mm. The temperature at the external was lower than that at the internal, so the external grew from the external to the internal while the direction of the internal was opposite. So there are lots of grain boundaries whose structure was irregular.

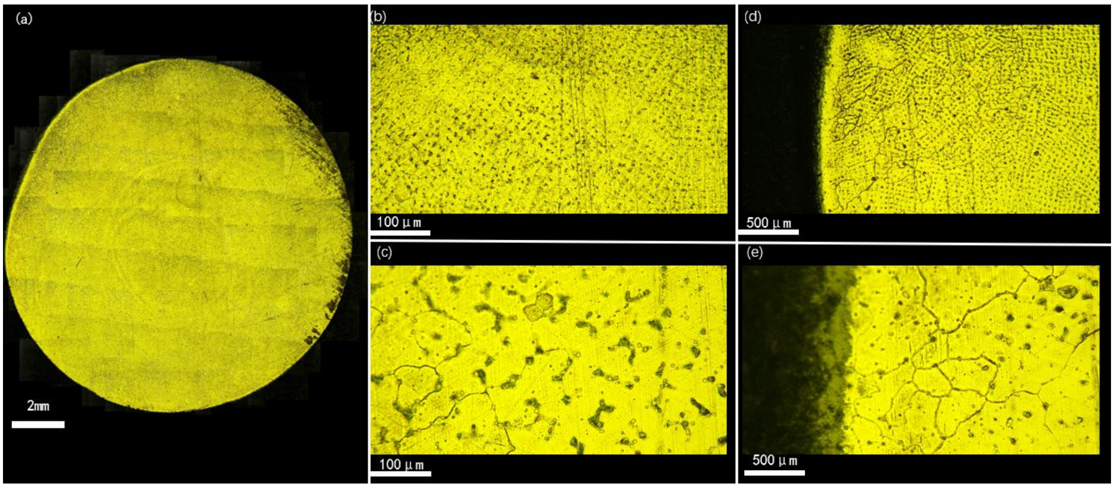

Figure 5. Microstructure at the light microscope (a) the cross section of sample (b) the center part of cross section ×50 (c) the center part of cross section r×200 (d) the external part of cross section ×50 (e) the external part of cross section ×200

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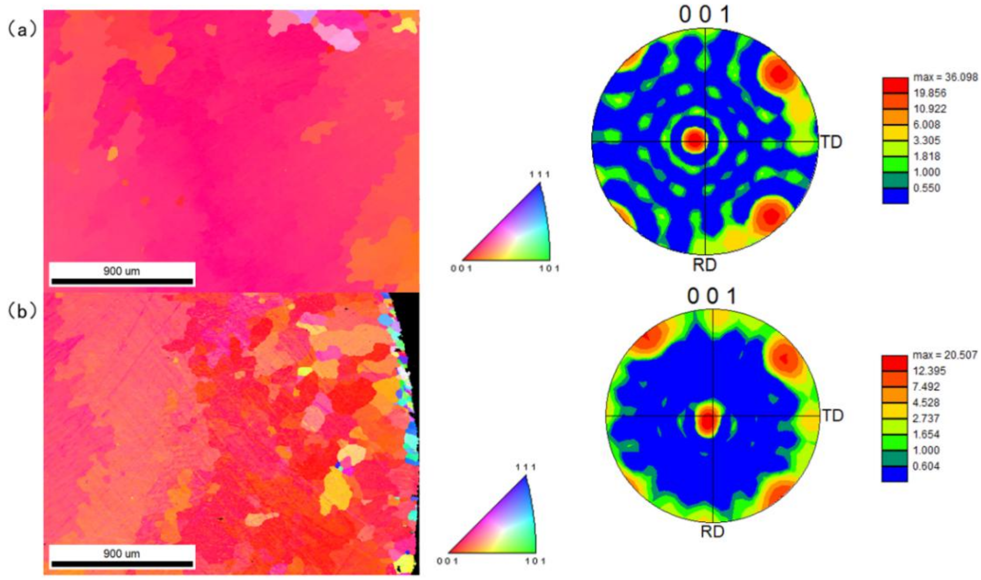
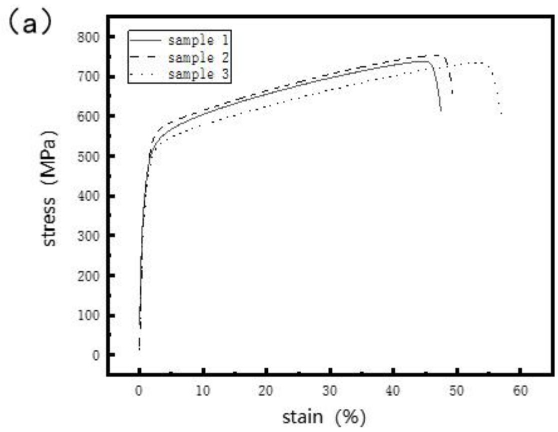


Figure 6. Electron Backscattered Diffraction (a) the center part of cross section; (b) the external part of cross section

The columnar crystal growth direction at the center shown as the EBSD (Fig.6a) is consistent to what we analyze before. And rotation angle had two obvious tendencies. The growth direction of the external was consistent which was parallel to the building direction, too, but the rotation angle was random. The distribution of boundaries was as what we analysis before. At the center, angle difference was about 7°-8° and the number was little while the external angle difference was bigger than 15° and the number of grain boundary is more. It was consistent with the temperature gradient that there was few differences about the heat flow at center while the external was in disorder.

3.4 Mechanical property

The mechanical properties are about GH4169 sample manufactured by WAAM which were tested in room temperature or 650℃ which was deposition or was heat treatment. The extensometer was also used in testing. The result was shown as Fig.7 and Table 3.



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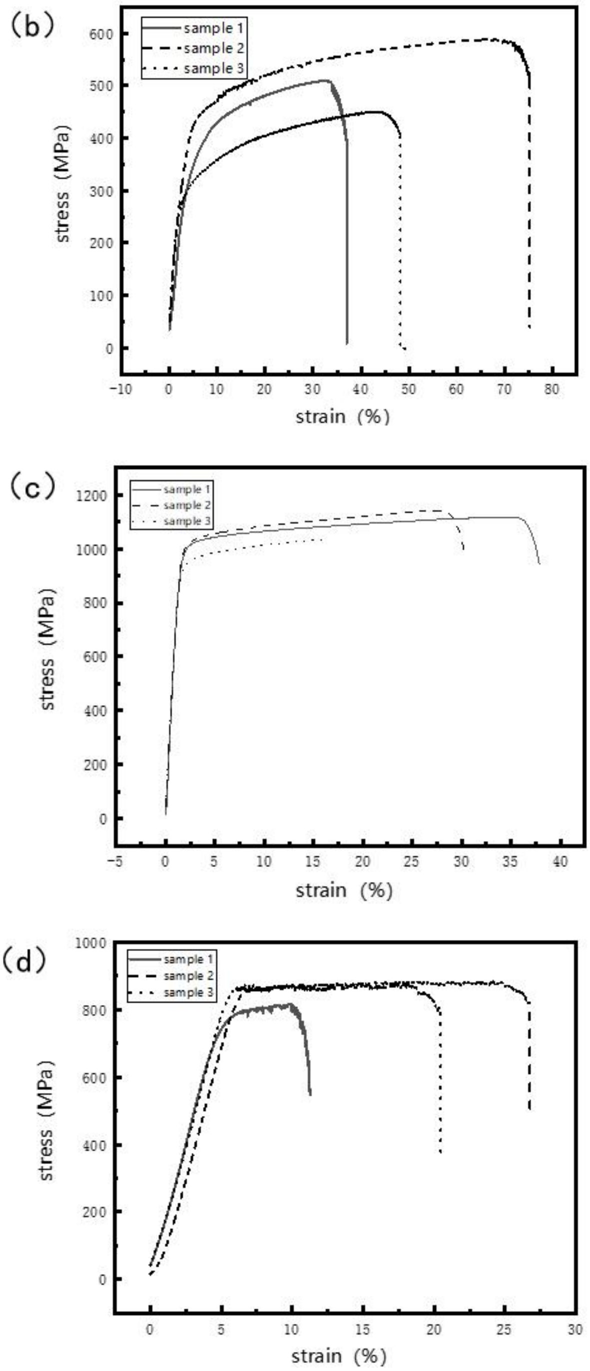

Figure 7. Stress-strain curve (a)the Dos at room temperature (DR);(b) the Dos at 650℃ elevated temperature (DE);(c) the HT at room temperature (HR);(d) the HT at 650℃ elevated temperature (HE)

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Table 3: Mechanical properties

	DR	DE	HR	HE	cast	Other WAAM
UTS (MPa)	736.67±10	515.67±65	1108±50	847.33±35	1280	1116
$YS_{0.2}$ (MPa)	396.33±15	296.33±50	943±35	809.67±60	1030	1065
Elongation (%)	32	27.5	24.83	15.17	12	90
Shrinkage (%)	57	56	39.33	33	15	/

The properties of the DR and DE was lower than the cast. This is because the number of grain boundaries induced. The grain boundary is the strengthening phase at the low temperature. So the method that promotes the controlled directional solidification of columnar crystals induced the number of boundaries and the sample's mechanical property is lower than casting whose grain boundaries were more. While the grain boundary induced the mechanical property at elevated temperature, so the mechanical property is not more excellent than others[22] (room temperature with heat treatment) that there are still a few grain boundaries.

The nickel base superalloy is more commonly used at elevated temperature, so the WAAM GH4169 is not more excellent than conventional cast material. The homogenisation treatment and aging heat treatment can improve the mechanical property, but it is also lower than cast. The additive manufacture process parameter can adjust growth direction of columnar crystal better until the growth directions are consistent and the elevated temperature mechanical property of it will be better.

4. Conclusion

The wire-arc additive manufacture can build the environment that promote the directed growth of columnar crystal by the method of layer by layer building. And several process parameters can control the environment and then change the tendency of the columnar crystal growth. The heat input and heating method will make a great influence.

(1) The center heating can maintain the stabilization of the center temperature and the growths direction of columnar crystals were almost consistent and grew from the center to the external while the external columnar crystals grew from the external to the center.

(2) There are few boundaries at the center while the number of grain boundaries at the external is large and morphologies of them are different.

(3) The number of grain boundary that strengthen the low temperature mechanical property decrease, so the property of WAAM sample is lower than that of casting whose boundaries were more at room temperature. While there are still grain boundaries, so the property of WAAM sample at elevated temperature is not excellent.

The growth of columnar crystal is influenced by all kinds of factor. The heat flow is the best important reason while others influence the growth by influencing the heat flow. If the heat flow is fit to columnar crystal growth, the epitaxial growth will appear. Heating method is also one kinds of way that can influence the heat flow. And it decides the growth direction of columnar crystal. So a fit heating method can promote the growth of objective crystal.

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