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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF WIRE ARC ADDITIVE MANUFACTURING Al – 5Si ALLOY

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Abstract. Al – 5Si alloy (4043), because of its good formability, high specific strength, and excellent corrosion resistance, is widely used in aerospace and automotive engineering. With the research and application of additive manufacturing technology such as wire/power laser additive manufacture, wire/power arc additive manufacture and so on. In this study, the Al – 5Si alloys have been used as raw materials for additive manufacturing research and wire arc additive manufacturing system equipped with 3D path simulation software, arc heat source and robot controlling platform is adopted to fabricate Al – 5Si alloy. The microstructure and mechanical properties of this Al – 5Si alloys are investigated. The x-ray diffraction results reveal that the as-deposited alloy is composed of α-Al, Si phase and intermetallic phase Al_9Si. According to optical microscope observation, it is found that as the deposition height increases, the eutectic Si phase is significantly coarsened and the columnar grains are gradually refining and transforming into finer equiaxed grains, and the grain size of the microstructure of the inter-layer regions is smaller than that of the inner-layer regions at any height. The average micro-hardness presents 47.5 ± 3.4 Hv, and the strength properties present only 1.6 – 5.0 MPa difference in ultimate tensile strength, 2.4 – 5.9MPa difference in yield strength and 0.1 – 1.1 % difference in elongation between tensile samples cut from different locations. It further indicates the better stability of wire arc additive manufacturing samples, and it is a better manufacturing method to fabricate metal parts.

Keywords: Al – 5Si alloy, microstructure, microhardness, tensile properties, wire arc additive manufacture

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Оригинальная статья

МИКРОСТРУКТУРА И МЕХАНИЧЕСКИЕ СВОЙСТВА ПРОВОЛОКИ ДУГОВОГО АДДИТИВНОГО ПРОИЗВОДСТВА СПЛАВА Al – 5Si

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Аннотация. Сплав Al – 5Si (4043) благодаря своей хорошей пластичности, высокой удельной прочности и отличной коррозионной стойкости широко используется в авиационном и автомобильном машиностроении. Это стало возможным, благодаря развитию и применению проволочных и дуговых технологий аддитивного производства. В настоящей работе сплавы Al – 5Si были использованы в качестве сырья для исследования аддитивного производства. Система дугового аддитивного производства, оснащенная программным обеспечением для моделирования 3D траектории, источником тепла дуги и платформой для управления роботом, была принята для изготовления сплава Al – 5Si. Исследованы микроструктура и механические свойства сплава Al – 5Si. Результаты рентгеновской дифракции показывают, что сплав состоит из α-Al, фазы Si и интерметаллической фазы Al_9Si. По данным оптического микроскопического наблюдения установлено, что с увеличением высоты осаждения эвтектическая фаза Si значительно огрубляется, столбчатые зерна постепенно измельчаются и превращаются в более мелкие равноосные зерна, а размер зерна микроструктуры межслоевых областей меньше, чем внутрислоевых областей на любой высоте. Средняя микротвердость составляет 47,5 ± 3,4 HV, а прочностные свойства отличаются только на 1,6 – 5,0 МПа по пределу прочности, 2,4 – 5,9 МПа по пределу текучести и 0,1 – 1,1 % по удлинению между образцами на растяжение, вырезанными из разных мест. Это также указывает на лучшую стабильность образцов, изготовленных методом аддитивного производства с использованием проволочной дуги, и на то, что это лучший метод изготовления металлических деталей.

Ключевые слова: сплав Al – 5Si, микроструктура, микротвердость, свойства при растяжении, проволочное дуговое аддитивное производство

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Introduction

Wire arc additive manufacturing (WAAM) is a direct energy deposition (DED) AM technology that uses arc welding as a heat source to melt the metal wire to deposit fabricated components layer-by-layer, which follows a model slice and a planned path. WAAM requires the following steps: building a CAD model, using 3D slicing software for model path planning and process parameter design, using a robotic or gantry system welding device for multi-layer deposition, and optional component post-processing operations [1 – 3]. Compared with powder-based additive manufacturing processes [4], WAAM has the advantages of high deposition rates, near-net-shape parts, reduced lead times and metal waste, low material costs and low setup costs [5 – 8]. Therefore, the WAAM process is more suitable for building many components than other AM routes [9 – 11]. In addition, the WAAM sample produced by the CMT process produced fewer pores, thus, the mechanical strength of the WAAM sample is improved.

In this study, Al – 5Si alloy was deposited using wire arc additive manufacturing based cold metal transfer (WAAM-CMT). The phase composition, microstructure, micro-hardness, and mechanical properties of the samples along the deposition height of Al–5Si samples had been investigated.

Materials and Methods

In the experiment, the bulk Al-5Si aluminum alloys with a dimension of 150 × 30 × 70 mm were deposited by WAAM-CMT system equipped with 3D path simulation software, Fronius CMT-Advance power source, 6-axis FANUC robot, wire feeder, Ar gas and a robot controller (Fig. 1, *a*), and the optimized parameter settings are as follows: ER4043 (Al – 5Si) alloy filler wire with a diameter of 1.2 mm was selected as the deposition material. The wire feed speed, deposition speed and Ar flow rate were set as 5.5 m/min, 0.6 m/min and 25 L/min, respectively. Before processing, the 6061-T6 aluminum alloy plate with the size of 200 × 60 × 10 mm was mechanically cleaned and fixed on the workbench as the base metal. The nominal chemical composition of BM and FW is listed in Table.1. The deposited samples and the schematic of sample positions for microstructural and mechanical tests are shown in Fig. 1, c. The cross section of the bulk alloy (sample e) for metallographic analysis was ground, polished, and etched with Keller's solution for about 15 seconds. The x-ray diffraction (XRD) and optical microscope (OM) were used for phase identification and microstructure analysis. Vickers micro-hardness tests were performed along the mid-height and the mid-width direction of samples, with 200 g force and an indentation dwells time of 10 s. Tensile tests of standard round tensile bars were carried out in a universal tensile testing machine at the loading rate of 2.0 mm/min. The secondary dendrite arm spacing, or the length of cellular grains and cooling rate were subsequently calculated by the Equation 1 [12].

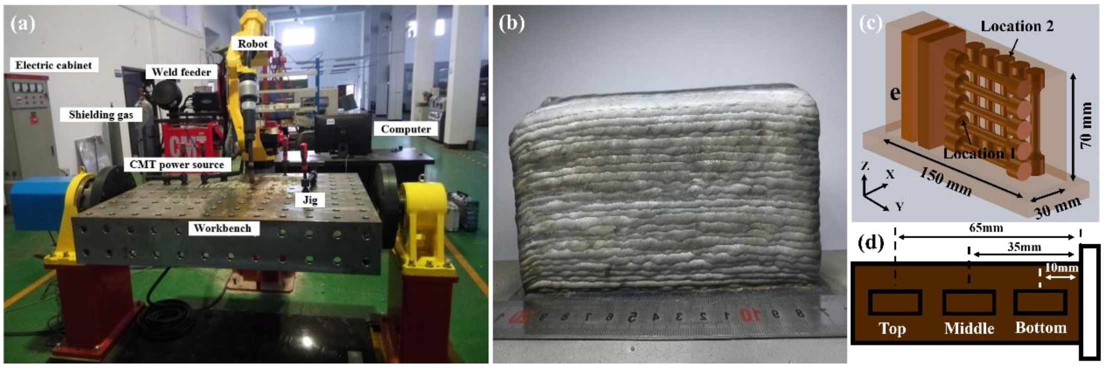

Fig.1 WAAM-CMT Al – 5Si alloys: (*a*) WAAM-CMT system; (*b*) Al – 5Si alloys sample; (*c*) schematic diagram of samples used for the tests; (*d*) the locations for micro-hardness samples; (*e*) the locations of sample used for micromorphology observation

FРис.1 WAAM-CMT сплавы Al – 5Si: (*a*) система WAAM-CMT; (*b*) образец сплава Al – 5Si; (*c*) схема образцов, используемых для испытаний; (*d*) расположение образцов микротвердости; (*e*) расположение образцов, используемых для микроморфологического наблюдения

Table 1. **Chemical composition of the ER4043 and 6061 alloy**

Таблица 1. Химический состав сплава ER4043 и 6061

Composition	Si	Fe	Cu	Mn	Mg	Al
ER4043	4.5～6.0	0.8	0.3	0.05	0.05	Balance
6061	0.4～0.8	0.7	0.15～0.4	0.15	0.8～1.2	Balance

$$L_{ave} = \frac{L_s N_s + L_c N_c}{2 N_c N_s}, \qquad (1),$$

where L_S is the length in μm and N_S is the number of dendrite arm spaces, L_C is the length of cellular grains and N_C is the number of cellular grains.

2.Results and Discussion

2.1 Microstructure

According to the XRD data in Fig. 2, *a*, the predominant phases in the WAAM-CMT Al-5Si samples with different deposition heights are α-Al, Si phase and intermetallic phase Al_9Si [13] and do not change. But a clear difference between the three regions can be seen in the α-Al phase. There is a strong main (111) crystal orientation peak in all samples, and both (200) crystal orientation peaks and (311) crystal orientation peaks have relatively high peaks, indicating that these are the main crystal orientations of the samples. At the same time, the crystal orientation peaks at the middle region are higher than those at the top and bottom regions, and the crystal orientation peaks at the top region are higher than those at the bottom region. This shows that the deposition height has an important influence on the crystal orientation.

Fig. 2, *b* shows the microstructure of Al – 5Si alloys along the deposition height. It can be found that after increasing the deposition height, although the microstructure heterogeneity did not change, the equiaxed to columnar ratio of the as-deposited samples is greatly improved. As the deposition height increases, the columnar grains are gradually refined and transformed into finer equiaxed grains, and the grain size of the microstructure of the TLRs is smaller than that of the NLRs at any height. In addition, with the increase in deposition height, the dendritic morphology of the α-Al phase is gradually refined and transformed into honeycomb-like grains both within and between layers. The eutectic Si phase is significantly coarsened, and the Si is spherical or square along the grain-boundary and the bounds show a discontinuous distribution. According to the measurement of dendritic arm spacing or honeycomb grains, it presents that the bottom regions in this study have approximately L_{ave} of 8.25 μm in the TLRs and 8.84 μm in the NLRs across 7 print layers. In contrast, there is the decreasing grain size (L_{ave}: 7.95 μm in the TLRs and 8.38 μm in the NLRs) in the top regions of sample (Table 2).

2.2 Micro-hardness

Fig. 3 depicts the micro-hardness distribution of the cross-section of the Al – 5Si alloy samples. As shown in Fig. 3, *a*, the micro-hardness measurement along the horizontal width of the Al-5Si alloy sample is selected, that is, the top region and the middle region and bottom region. There is a periodic change in the micro-hardness value with the deposition height. Among them, the average micro-hardness value of the top region of the sample is 50.7HV, the average micro-hardness value of the middle region of the sample is 48.5HV, and the average micro-hardness value of the bottom region of

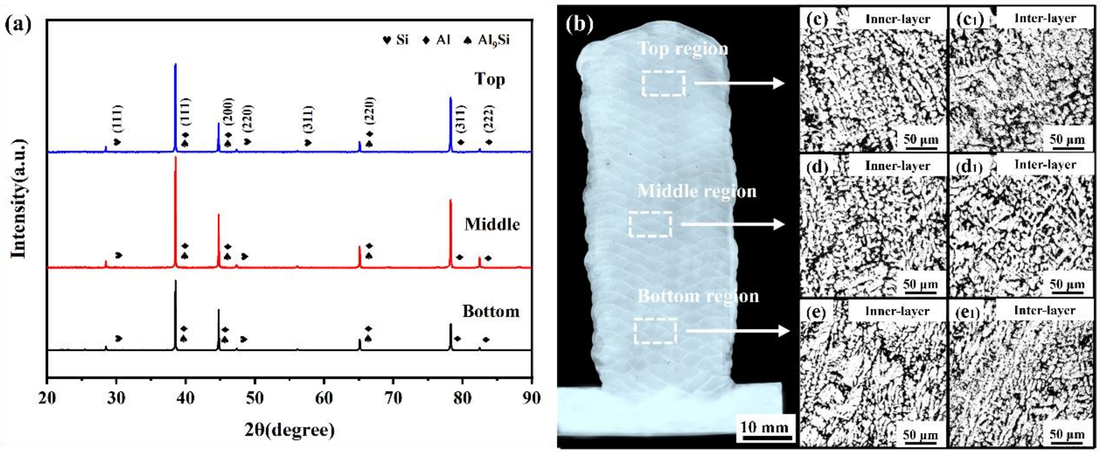

Fig. 2 (*a*) the XRD results of WAAM-CMT Al – 5Si alloys; (*b*) the microstructures of WAAM-CMT Al – 5Si alloys under different regions

Рис. 2 результаты рентгеноструктурного анализа сплавов WAAM-CMT Al – 5Si; (*b*) микроструктуры сплавов WAAM-CMT Al – 5Si в различных областях

Table 2. **The grain size of Al-5Si alloys in NLR/TLR**

Таблица 2. **Размер зерна сплавов Al-5Si в NLR/TLR**

Sample	L_{ave} – NLRs, µm	L_{ave} – TLRs, µm
Bottom region	8.84	8.25
Middle region	8.53	8.11
Top region	8.38	7.95

the sample is 43.3HV. With the increase of the deposition height, the micro-hardness value of the sample shows an increasing trend, and the micro-hardness value on the uniform horizontal line does not change much, and the micro-hardness changing value is 3.4 HV, which further indicates the stability of the deposition sample. At the same time, as shown in Fig. 3, *b*, the micro-hardness measurement along the mid-height of the Al – 5Si alloy. Pores, cracks and equiaxed grains are more prone to product around TLRs, resulting in lower micro-hardness at defect sites and higher micro-hardness in the equiaxed grain region. In the mid-high direction near the base metal and the top region of the sample, the micro-hardness values are higher in both the TLRs and NLRs due to the formation of finer grain sizes [14].

2.3 Tensile properties

Tensile test results (tensile strength-UTS, yield strength-YS and elongation-E) of two different regions of alloy samples are shown in Fig. 4. Tensile test results on the top region of the samples are different from those on the bottom region of the sample. The tensile strength of the samples increases by 6.6 MPa from 205.6 to 212.2 MPa as the increase of

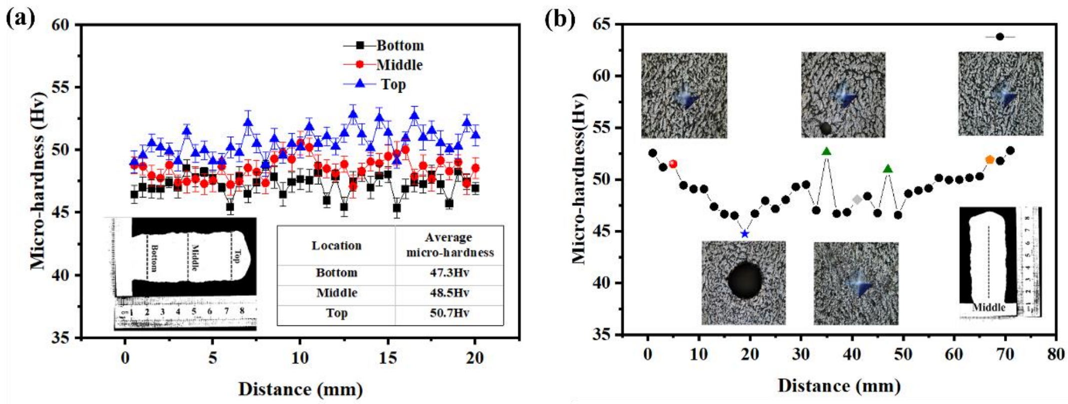

Fig. 3 The micro-hardness of WAAM-CMT Al – 5Si alloys along horizontal width (*a*) and mid-height (*b*) directions

Рис. 3 Микротвердость сплавов WAAM-CMT Al – 5Si в горизонтальном направлении по ширине (*a*) и средней высоте (*b*)

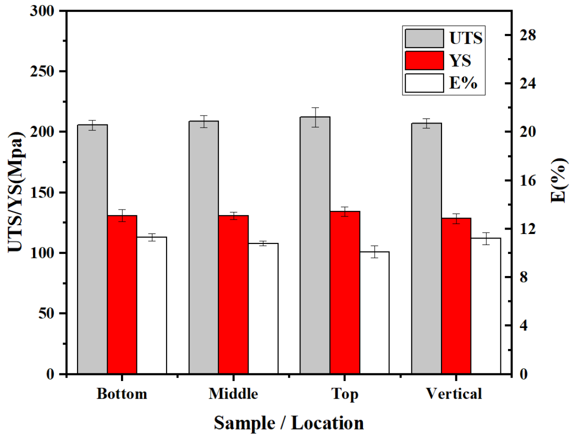

Fig. 4 The tensile properties of WAAM-CMT Al – 5Si alloys

Рис. 4 Растяжимость сплавов WAAM-CMT Al – 5Si

deposition height. The yield strength also increases from 130.9 to 134.4 MPa with the elongation is relatively reduced by 1.3 %. Analysis of tensile test results show that the increase in deposition height improve the tensile properties of the Al – 5Si alloys. Besides, the tensile strength and yield strength in the location 1 are also higher than those in the location 2.

The fracture morphology of the Al – 5Si sample is shown in Fig. 5. The fracture analysis reveals the characteristics of ductile fracture. Fig. 5, *c*, *d* show that the second phase particles are uniformly distributed at the center of the dimples of the fracture. The cracking of the alloy matrix is caused by the second phase particles and interlayer defects – pores and cracks. During the tensile test, the stress is concentrated in the second phase particles and interlayer defects. As the stress increases, microcracks and microcrack propagation may appear in the structure. These microcracks connect with each other, grow up and cause the material to fracture [15].

3. Conclusions

In the current work, the phase formation, microstructure, and mechanical properties of WAAM-CMT Al – 5Si alloy samples along the deposition height have been investigated. The main phases include α-Al, Si phase and intermetallic phase Al_9Si,

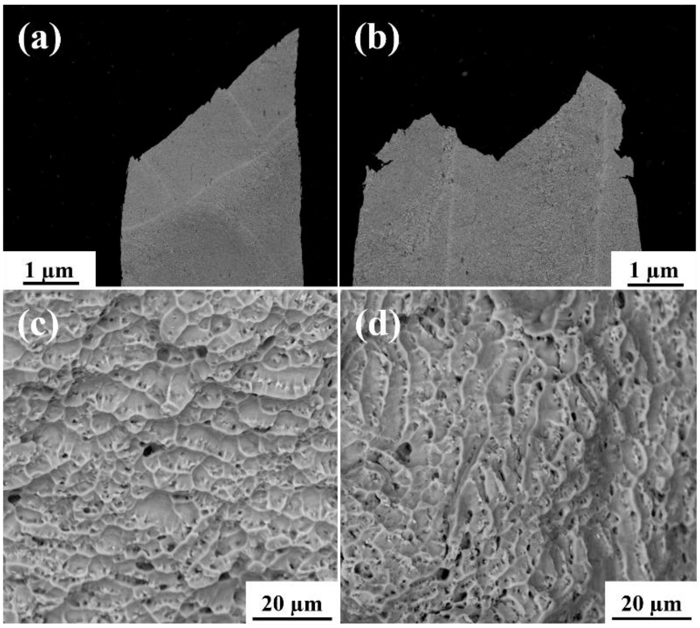

Fig. 5. Fracture surface images of WAAM-CMT Al – 5Si alloys at location 1 and location 2

Рис. 5. Изображения поверхности излома сплавов WAAM-CMT Al – 5Si в точках 1 и 2 the α-Al phase is gradually refined and transformed into honeycomb-like grains both within and between layers. The higher micro-hardness and strength of Al – 5Si alloys among all samples are attributed to the equiaxed grains with coarsened Si phases and less defects. The analysis of tensile test results among different deposition heights shows that the increase in deposition height improve the ultimate tensile strength of the Al – 5Si alloys. But the little difference in performance indicates the stability of the Al – 5Si alloys are better.

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