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ARTICLE

Effects of Fe Content on Microstructure and Properties of Al-7Si-0.6Mg Alloy Fabricated by Wire Arc Additive Manufacturing

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Abstract: The effect of Fe addition on the structure and properties of Al-7Si-0.6Mg alloy fabricated by wire arc additive manufacturing (WAAM) was studied, and the morphology and distribution of Fe-rich phase in the alloy were observed. The results show that the finely acicular Fe-rich phase in as-deposited alloys is a mixture of metastable Mg-Si phase and π-Fe phase. After heat treatment (T6), Mg_2Si dissolves from Fe-rich phase and forms π-Fe phase. With the increase of Fe addition, the size and quantity of Fe-rich phase in the alloy increase. The small change of Fe-content can have a great effect on the elongation of WAAM alloy (T6), but it has no obvious effect on strength. As the Fe content increases from 0.109 wt% to 0.177 wt%, the fracture elongation of the alloy decreases by 47.1%.

Key words: wire arc additive manufacturing (WAAM); Al-7Si-0.6Mg alloy; microstructure and properties; π-Fe phase

Wire arc additive manufacturing (WAAM) is a technology that melts metal wires and accumulates solid parts layer by layer under the action of arc. Because only a part of the molten pool is in liquid state during the manufacturing process of structural parts, and the temperature difference between the molten pool and the surrounding environment is large, the cooling rate in the forming process is very high. It has become one of the low-cost rapid prototyping methods for large aluminum alloy parts[1-4]. In recent years, more and more attention has been paid to the research of WAAM process of aluminum alloys, including Al-Mg[4-6] and Al-Cu[7-11] alloy systems.

Al-7Si-0.6Mg alloys are widely used in automotive and aerospace[12-15] industries due to their excellent castability and corrosion resistance. In particular, Al-7Si-0.6Mg alloy can have good mechanical properties after heat treatment, and its amount accounts for more than 80% of the total production of aluminum alloy castings. Therefore, it is necessary to carry out the research on the WAAM technology of Al-7Si-0.6Mg alloy. Yang et al[16] believe that heat treatment is an effective method to control the microstructures and to improve the comprehensive mechanical properties of WAAM Al-7Si-0.6Mg alloy. Li et al[17] reported the structure and properties of ZL114A (Al-7Si-0.6Mg) formed by WAAM process, and they found that WAAM alloy has better properties than casting alloy. Amberlee et al[18] studied the modification of 4943 and 4047 alloys by Mg, Sr, TiB and their combination to adapt to the GMAW-based 3D printing process. The solubility of Fe as impurity in Al-Si-Mg alloy is very low[19]. Fe-rich intermetallic compounds such as *α*-Fe (Al_8SiFe_2), *β*-Fe (Al_5SiFe) and π-Fe ($Al_8Mg_3FeSi_6$) are formed during the solidification process of the alloy[20-24]. These intermetallic compounds can split the structure of the aluminum matrix and cause stress concentration and promote crack initiation under the action of external forces. In particular, acicular *β*-Fe phase is the most harmful. The main methods to reduce the harm of Fe in

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Al-Si-Mg alloy include controlling the content of Fe[25-26] and improving the morphology of Fe-phase in the alloy[27-32]. In the solidification process of the alloy, the effect of Fe-phase on the morphology is very significant with increasing the cooling rate[30-32], which can reduce the length of plate-like Fe-phase and weak the effect of Fe-phase on the properties of the alloy. The WAAM process has the characteristics of fast melting and rapid cooling. The solidification of alloy is under extreme non-equilibrium condition. Therefore, it is necessary to study the effect of Fe content on the microstructure and properties of the alloy.

The upper limit of Fe content in Al-7Si-0.6Mg alloy is 0.20 wt% and 0.19 wt% according to the standards of GB/T 1173-2013 and ISO 3522-2006, respectively, so the range of Fe content studied in this experiment is less than 0.19 wt%. The purpose of this work is to provide theoretical and data support for designing the upper limit of Fe content in Al-7Si-0.6Mg material for WAAM and the engineering application of WAAM Al-7Si-0.6Mg alloy.

1 Experiment

ER4220 welding wire (Φ=1.2 mm, provided by NEIMM) was selected as raw material. The WAAM forming process was CMT (cold metal transfer)+Plus (as shown in Fig.1) and forming path was single layer and multi-channel. The processing parameters are listed in Table 1. The as-deposited alloys were treated through T6 heat treatment (540 °C, 12 h, 175 °C and 4 h). Cutting tools, e.g. water knife, band saw and wire cutting, were used to cut the stretching sample of sheet shape. The sampling position of stretching sample is shown in Fig.2, and the size is shown in Fig.3.

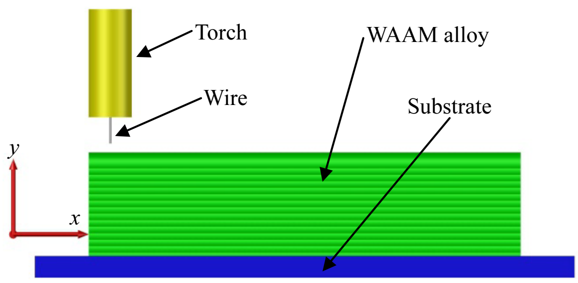

Fig.1 Diagram of WAAM process

Table 1 Process parameters WAAM forming process

Forming process	Wire feed speed/m·min^{-1}	Travel speed/mm·s^{-1}	Gas flow rate/L·min^{-1}	Current/A	Voltage/V
CMT+Plus	6.0	10	25	120~130	20.4~21.4

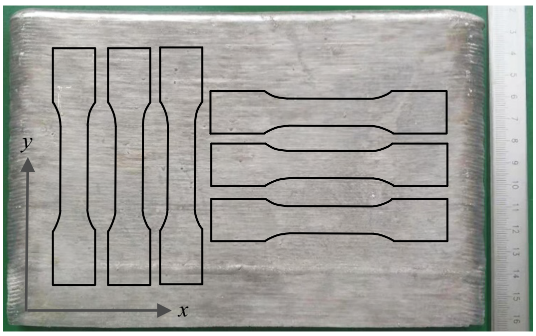

Fig.2 Diagram of sampling position

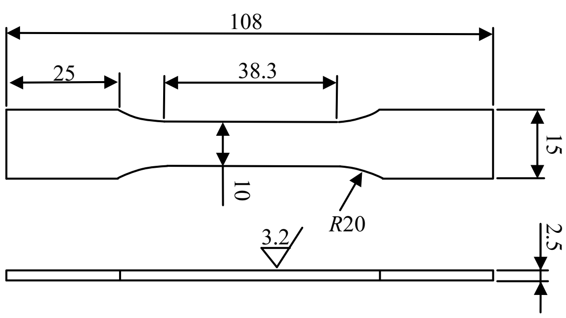

Fig.3 Schematic diagram of tensile test sample size (mm)

Three parallel samples were taken from each group of WAAM alloys after T6 heat-treatment and tensile properties were tested by universal testing machine (WDW-30). The metallographic samples were cut from the as-deposited alloys and the T6 heat-treated alloys, and the microstructure was observed by metallographic microscope (Axio Imager A2m); the fracture morphology and EDS energy spectrum of the tensile samples were observed by scanning electron microscope (CamScan-3400), and the microstructure was observed by electron probe (EPMA-1720H). Phase analysis of the WAAM alloy was conducted using an X-ray diffractometer (Rigaku D/max 2500/PC). Wavelength dispersive spectrometer (WDS) was used to analyze the Fe-phase composition.

2 Results and Discussion

2.1 Chemical composition

The chemical composition of raw material ER4220 and Al-7Si-0.6Mg-*x*Fe (WAAM) alloys is shown in Table 2. Compared with ER4220 welding wire, Mg content in the WAAM alloy decreases slightly and Fe content increases slightly. This is because Al, Mg and other elements are burned by high-temperature arc and volatilized in the forming process of the alloy. By comparing the chemical composition changes of the four groups of raw materials and WAAM samples, it is found that the Fe content in WAAM Al-7Si-0.6Mg alloys can

Table 2 Chemical composition of ER4220 welding wire and WAAM alloys (wt%)

	Sample	Si	Mg	Ti	Fe	Sr	Al
1#	Raw material	6.98	0.672	0.114	0.104	0.029	Bal.
	WAAM alloy	7.01	0.614	0.112	0.109	0.028	Bal.
2#	Raw material	7.15	0.668	0.128	0.124	0.031	Bal.
	WAAM alloy	7.18	0.604	0.117	0.131	0.030	Bal.
3#	Raw material	7.05	0.703	0.123	0.153	0.032	Bal.
	WAAM alloy	7.15	0.664	0.119	0.159	0.029	Bal.
4#	Raw material	7.03	0.713	0.121	0.172	0.028	Bal.
	WAAM alloy	7.20	0.697	0.117	0.177	0.030	Bal.

be controlled by controlling the Fe content in the raw materials, so as to control the structure and performance of the WAAM alloys.

2.2 Pores and microstructure

The porosity distribution of as-deposited WAAM alloys with different Fe contents is show in Fig.4. With the increase of Fe content, the size and number of pores have no significant change.

Fig.5 shows the metallographic structure of as-deposited WAAM Al-7Si-0.6Mg alloy with different Fe contents. Fig.6 illustrates the XRD results of 4# alloy. It can be seen that the alloys are mainly composed of the α-Al matrix, fibrous eutectic silicon, Mg_2Si and fine needle-like Fe-rich phase. Fig.7 shows the metallographic structure of WAAM Al-7Si-0.6Mg alloy after heat treatment (T6), in which the eutectic silicon is spheroidized and dispersed evenly, and then acicular Fe-rich phase is coarsened. The size and quantity of Fe-phase in the alloys increase with the increase of Fe content in the alloys both in as-deposition state and T6 state.

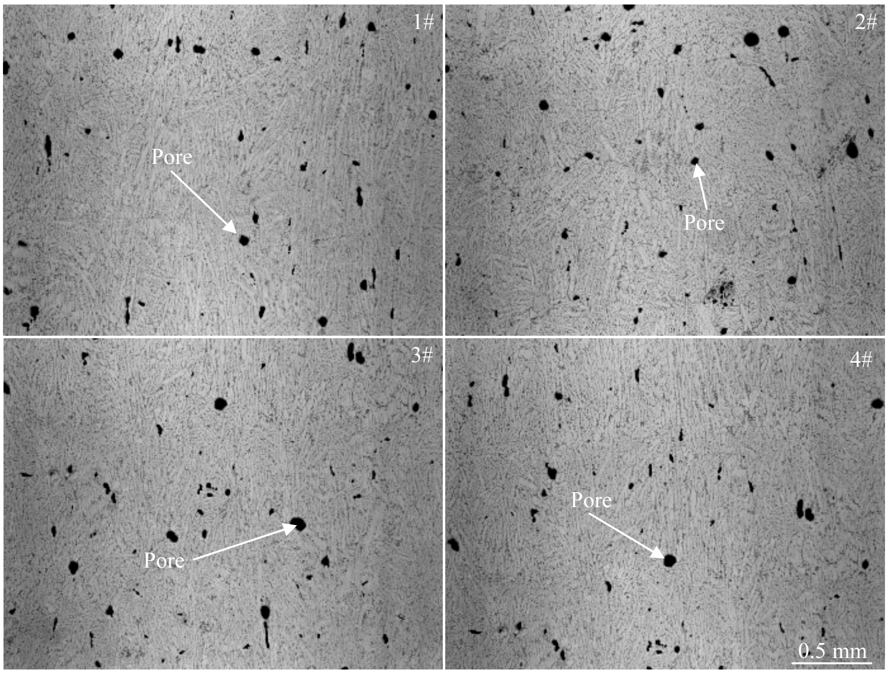

Fig.4 Porosity distributed of as-deposited WAAM alloys

EPMA images (4# sample) of as-deposited alloy and heat-treated alloy (T6) are shown in Fig.8. Table 3 shows the WDS analysis results of needle-like Fe-rich phase in the as-deposited alloy and rod-like Fe-rich phase (T6 heat-treat). The results show that the composition of Fe-rich phase in the as-deposited alloy is $Al_{36}Mg_{3.9}FeSi_{7.4}$, and the atomic ratio of Mg, Si to Fe is higher than that of π-Fe phase ($Al_8Mg_3FeSi_6$). The Fe-rich phase after heat treatment (T6) is $Al_{18.5}Mg_3FeSi_{5.5}$, which is identified as the π-Fe phase according to the XRD results.

WAAM process is a fast melting and rapid solidification process, so the cooling rate is very fast and the secondary dendrite spacing of solidified structure is small. As shown in Fig.5, the dendrite boundary area (per unit volume) of solidified structure becomes larger, and the remaining liquid area becomes thinner and splits into a large number of isolated channels, which prevent intermetallic compounds from joining and refine the Fe-rich intermetallic compound phase. During the solidify-cation process, Mg, Si and Fe form a mixture of metastable Mg-Si phase and π-Fe phase (Fe-rich phase)[33] in the eutectic region consisting of $Al_{36}Mg_{3.9}FeSi_{7.4}$. As the content of Mg is higher than 0.6 wt% under the experimental conditions, the formation of the π-Fe phase is accelerated, so the formation of the β-Fe phase cannot be carried out or only has a trace amount[33]. With the increase of Fe content, the size and quantity of π-Fe intermetallic compounds increase. During the solidi-fication process, a large number of Mg_2Si precipitates reach the

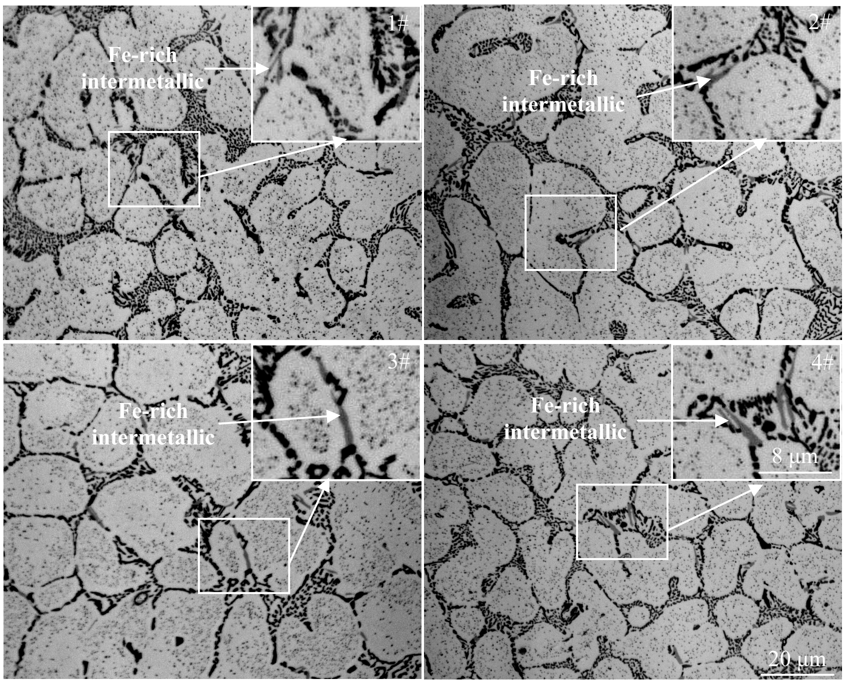

Fig.5 Metallographic structure of as-deposited WAAM alloys

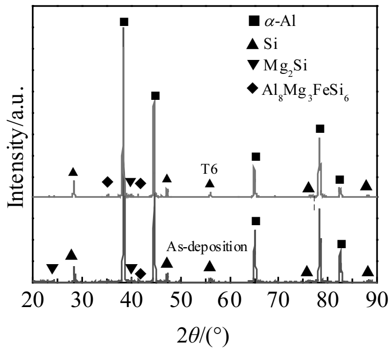

Fig.6 XRD patterns of 4# alloy in as-deposition and T6 state

limit solubility of magnesium in the matrix of α-Al, which inhibits the diffusion kinetics of magnesium from the mixed phase to the matrix of α-Al during the solid solution heat treatment process. Therefore, only Mg_2Si phase dissolves in Fe-rich phase, and meanwhile, the amount of π-Fe phase remains almost unchanged, and only a small part is transformed to β-Fe phase[34]. The coarsening of π-Fe phase after heat treatment (T6) is mainly attributed to the dissolution of Mg_2Si in Fe-rich phase and the aggregation of fine Fe-rich phase around it.

2.3 Mechanical testing

2.3.1 Tensile properties

The mechanical properties of tensile samples of WAAM Al-7Si-0.6Mg-xFe (T6) alloy are tested, as shown in Fig.9. Based on the average values of horizontal (H) and vertical (V) ultimate tensile strength (UTS), yield strength (YS) and elongation of alloys with different Fe contents, it can be seen that there are no significant differences in horizontal and vertical mechanical properties. With the increase of Fe content, the YS increases slightly and the elongation decreases. As the Fe content increases from 0.109 wt% (1#) to 0.177 wt% (4#), the YS of the alloy increases by 5.5% and the elongation decreases by 47.1%. Therefore, considering the economy and the requirements of aerospace standard QJ3185 for mechanical properties of class Ⅰ castings of this kind of alloy, it is suggested that the Fe content of raw material should be controlled below 0.131 wt% (2# alloy).

With the increase of Fe content, the morphology of fine Fe-phases in WAAM Al-7Si-0.6Mg (T6) samples become coarser and the number increases, which plays a second phase strengthening role and makes the YS of the alloy slightly increase. Under the effect of external force, coarsened Fe-phases make the cracks easier to form and expand, obviously weakening the strengthening effect, and especially, ductility is severely deteriorated.

2.3.2 Fracture morphology

The tensile fracture surface of 4# samples (T6) is shown in Fig.10. The fracture is characterized by ductile fracture. Secondary cracks are found at the fracture by high magnification observation. EDS results confirm that the secondary cracks are surrounded by Fe containing phase. Aluminium matrix is fractured by brittle and hard Fe-phase. Under the

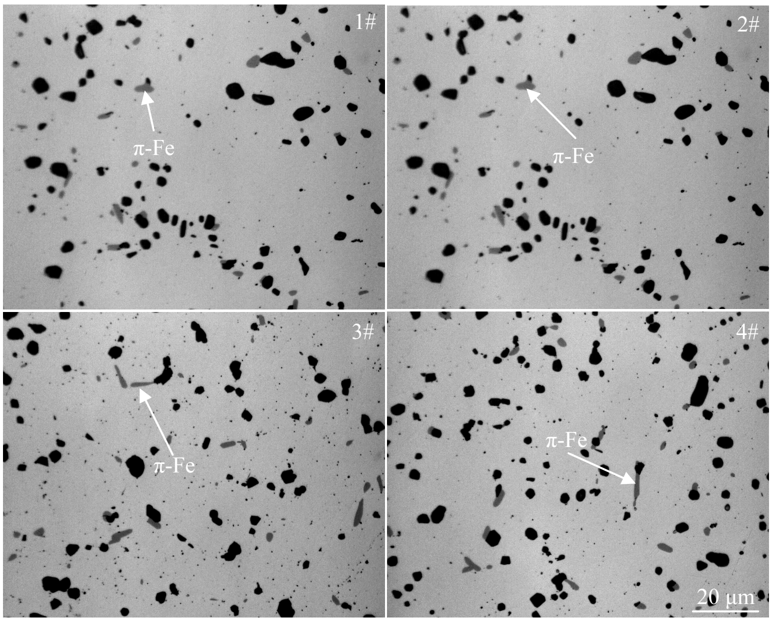

Fig.7 Metallographic structure of WAAM alloys after T6 treatment

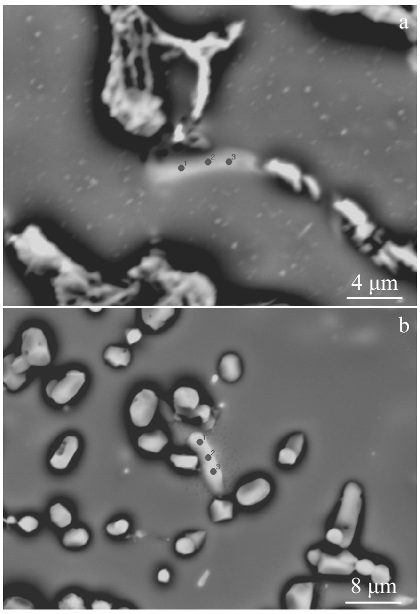

Fig.8 EPMA images of as-deposited (a) and T6 treated (b) 4# sample

Table 3 WDS analysis of Fe-rich phases in as-deposited and T6 treated alloys

Element	As-deposition		T6 heat-treat	
	wt%	at%	wt%	at%
Mg	7.063	8.002	9.212	10.593
Al	73.131	74.628	63.809	66.090
Si	15.606	15.300	19.846	19.748
Fe	4.203	2.071	7.133	3.569

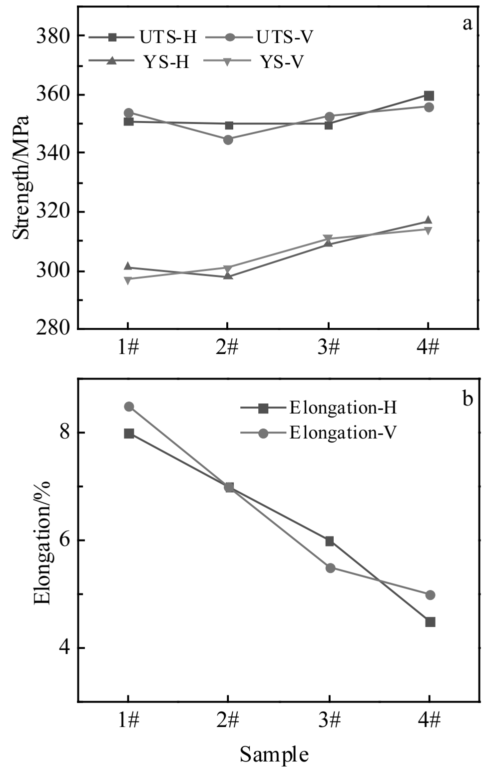

Fig.9 Mechanical properties of WAAM Al-7Si-0.6Mg alloy (T6): (a) strength and (b) elongation

action of external stress, cracks are easier to form. In addition, the tip of ferrous phase is a high stress concentration point. Cracks can nucleate in aluminium matrix and propagate through Fe containing phase under loading.

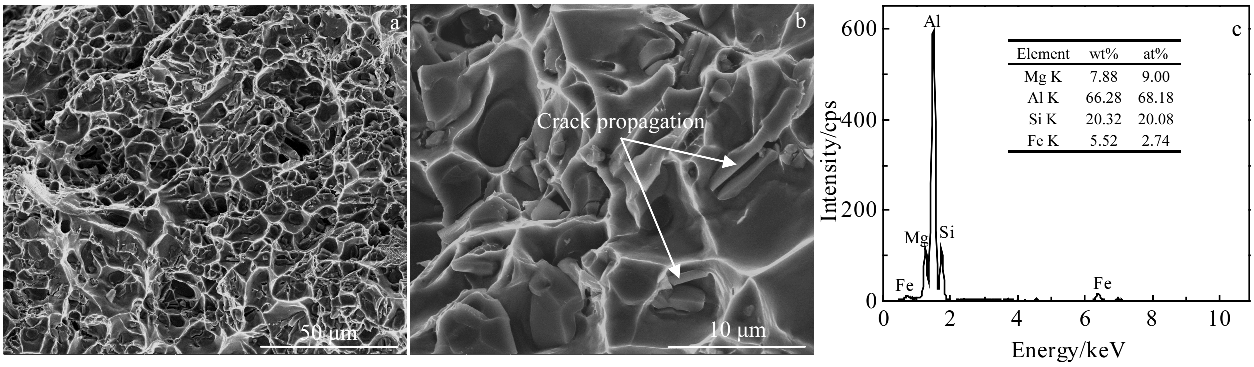

Fig.10 SEM images (a, b) and EDS analysis (c) of vertical tensile fracture of 4# alloy

3 Conclusions

1) The Fe content in WAAM Al-7Si-0.6Mg alloys can be controlled by controlling the Fe content in the raw materials, thereby controlling the structure and performance of the WAAM alloys.

2) In as-deposited WAAM Al-7Si-0.6Si alloy, Fe mainly exists in the metastable mixed phase with the composition of Mg-Si phase and π-Fe phase, which is composed of $Al_{36}Mg_{3.9}FeSi_{7.4}$. During the solution treatment, Mg_2Si dissolves from Fe-rich phase and forms π-Fe phase. With the increase of Fe content, the size and quantity of Fe-rich phase in as-deposited and heat treated (T6) alloys increase.

3) The change of Fe-content in a small range can have a great effect on the elongation of WAAM alloy. As the addition of Fe increases from 0.109 wt% to 0.177 wt%, the fracture elongation of the alloy decreases by 47.1%.

4) Considering the economy and comprehensive properties of WAAM alloy, it is suggested that the Fe content of raw material should be controlled below 0.131 wt%.

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Fe 含量对电弧增材制造 Al-7Si-0.6Mg 合金组织与性能的影响

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摘　要：研究了 Fe 含量对电弧增材制造（WAAM）Al-7Si-0.6Mg 合金组织与性能的影响，并观察了合金中富 Fe 相形貌和分布。结果表明，WAAM 成形试样中富 Fe 相为细小针状，为亚稳态镁硅相和 π-Fe 相的混合相。经 T6 热处理后，富 Fe 相中 Mg_2Si 脱溶而形成 π-Fe 相。随着 Fe 含量的增加，合金中富 Fe 相的尺寸增大、数量增多。Fe 含量在较小的范围内变化即可对 WAAM 成形合金的延伸率产生较大影响，而对强度作用不明显，当 Fe 含量由 0.109%（质量分数）增加到 0.177%，合金的断裂延伸率降低了 47.1%。

关键词：电弧增材制造 (WAAM)；Al-7Si-0.6Mg；组织与性能；π-Fe 相

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