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Improved corrosion behavior of ultrafine-grained eutectic Al-12Si alloy produced by selective laser melting

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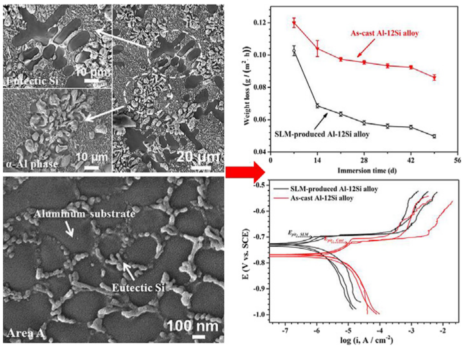
HIGHLIGHTS

- The corrosion behavior of selective laser melted (SLMed) Al-12Si is investigated.
- Ultrafine-grained eutectic Si particles are observed in SLMed Al-12Si alloy.
- SLMed Al-12Si has much better corrosion resistance than the cast counterpart.

GRAPHICAL ABSTRACT



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ABSTRACT

Although the parts produced by selective laser melting (SLM) are reported to possess comparable or better mechanical properties than the traditionally processed counterparts, the SLM-produced parts demonstrate slightly unfavorable corrosion resistance properties compared with their traditional counterparts. This work shows that, in addition to rapid manufacturing of parts, SLM can effectively refine the grains of eutectic Al-12Si alloy. The SLM-produced Al-12Si shows an ultrafine-grained microstructure and improved corrosion resistance, which provides an innovative and efficient approach to refine the silicon particles in eutectic Al-12Si alloy. Unlike the microstructured Al-12Si alloy manufactured by traditional casting, the SLM-produced Al-12Si alloy contains ultrafine-grained eutectic silicon particles distributing in the aluminum substrate. Importantly, it is found that the SLM-produced Al-12Si alloy possesses superior corrosion resistance than the cast Al-12Si alloy in terms of the results from electrochemical methods and weight loss test. The favorable corrosion resistance of SLM-produced Al-12Si is attributed to these ultrafine silicon particles, which prominently benefits for the formation of the oxide film. The influence of the microstructure with regard to eutectic silicon particles size on the corrosion resistance has also been discussed in depth.

1. Introduction

Among all the aluminum alloys, Al-12Si alloy is one of the most suitable candidates for automobile parts, such as the engine pistons, auto

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hubs and crankcases. Such widespread applications are triggered thanks to the low thermal expansion coefficient, superior wear resistance and high specific strength of Al-12Si alloy [1–4]. Some previous studies [5,6] have also shown that Al-12Si alloy castings possess high impact resistance and high load capacity, which greatly enhance the service life of castings. However, it is known that a low cooling rate adopted during traditional fabrication allows sufficiently long time for the element silicon to diffuse thereby forming acicular or coarse eutectic particles in the microstructure of an aluminum part. This could significantly deteriorate the aluminum substrate, which extremely weakens the mechanical properties of the traditionally processed Al-12Si alloy and greatly limits its long-term applications in some specific environments [7,8]. In order to improve its mechanical properties, a great deal of work has been conducted to study the refinement of silicon particles in Al-12Si alloy. For example, it has been reported that complex modification (e.g. by adding rare earth elements into the alloy) could effectively suppress the growth of eutectic silicon particles, resulting in formation of ultrafine particles [9]. However, this method may also introduce new elements thus degrades the castability (i.e. flow-ability and compactness). Therefore, it seems that enhanced mechanical properties and favorable castability cannot co-exist for the Al-12Si alloy.

However, there is no such problem when using selective laser melting (SLM) to manufacture Al-12Si alloy. As one of the layer-wise additive manufacturing (AM) processes, SLM technique builds the components layer-by-layer through sequentially melting metallic powder on the platform by a focused laser beam and followed by rapid solidification into a solid layer [10,11]. Compared to the traditional fabrication techniques, SLM offers some overwhelming advantages, namely simpler manufacturing process (requiring no machining tools), higher material utilization (more than 80%) and higher level flexibility (arbitrary shape) [12–14]. Considering these characteristics, SLM has been applied to some aspects of daily life and industrial production, such as engine impeller, earphone diaphragm, circuit element and airplane tail [10,15,16].

Importantly, another major advantage of this novel technique is the extremely high heating and cooling rate in the SLM process, which could effectively suppress the sustained growth of the alloy elements (Si, Fe, Mn, Sn, etc.) and form substantially ultrafine-grained particles in the substrate of the SLM-produced components [7,17–20]. Because of this remarkable advantage, many researchers have indeed produced the eutectic Al-12Si alloy with improved mechanical properties by employing SLM. For instance, Prashanth et al. [21] have reported that SLM-produced Al-12Si alloy possesses high yield strength reaching about 260 MPa, which is more than four times that of the corresponding traditionally as-cast counterparts. Suryawanshi et al. [5] have found that the SLM-produced Al-12Si alloy exhibits a prominent enhancement in the fracture toughness in comparison to the same alloy produced by casting. Li et al. [7] also have observed that the SLM-produced Al-12Si alloy has far higher tensile properties than the cast alloy. Furthermore, previous studies showed that the corrosion property of casting Al-12Si alloy is relatively poor on account of the coarse-grained silicon particles [22–24]. Therefore, there is still an open question: could the SLM technique prepare Al-12Si alloy with ultrafine eutectic silicon particles overcome the demerit of as-cast alloy and show enhanced corrosion resistance? Unfortunately, there is a lack of such a research regarding the corrosion behavior of SLM-produced Al-12Si alloy.

As such, in this work, SLM is employed to prepare the eutectic Al-12Si alloy with the ultrafine-grained microstructure. The difference of corrosion behavior between the SLM-produced Al-12Si alloy and its traditionally cast counterpart has been systematically investigated. The weight loss test and electrochemical measurements are used to investigate the corrosion resistance properties of two types of Al-12Si alloy in NaCl solution. Microstructural characterizations are also performed to underpin the understanding of the relationship between the corrosion resistance and the size of silicon particles.

2. Experimental

2.1. Materials preparation

Two types of Al-12Si (wt%) alloy samples were prepared by different processes for use in this work. One was the as-cast Al-12Si alloy bar, and the other was the Al-12Si alloy cube (size of 10 mm × 10 mm × 10 mm) produced by SLM. Note that all SLM-produced samples mentioned in this work were the top view (i.e. XY-plane or build plane) of SLM-produced Al-12Si alloy.

As for the SLM process, Al-12Si (wt%) powder (TLS Technik, Germany) with an average particle diameter of 38 μm was used. The SLM process was performed using an in-house Realizer SLM-250 machine (Realizer GmbH, Germany) equipped with a 300 W Yb: YAG fiber laser, generating a laser beam with the power (at the part bed) of 200 W ($\lambda = 1.06$ μm) and the beam diameter of about 80 μm spot size. The high purity argon protection atmosphere was used during the SLM process to avoid oxygen contamination. The power of laser, thickness of layer, laser scan speed and hatch spacing (distance between scan lines) used for producing Al-12Si cubes were fixed at 200 W, 50 μm, 1600 mm/s and 105 μm, respectively. For the SLM-produced Al-12Si alloy, no pre-heating was applied to the substrate and a "Zigzag" laser scanning pattern (i.e. rotation by 90° was used upon the precedent layer) was used in the process of SLM. In addition, the density of SLM-produced Al-12Si cubes was measured using the Archimedes method and the relative density was greater than 99.5%. Table 1 lists the nominal chemical compositions (wt%) analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Australia) for the SLM-produced Al-12Si alloy and the as-cast Al-12Si alloy. As seen from Table 1, the compositions of both alloy samples were very close.

Samples with a dimension of 10 mm × 10 mm × 5 mm were cut from the SLM-produced Al-12Si cubes and as-cast Al-12Si bar, respectively. Prior to the electrochemical measurements, all alloy samples were connected to the copper line by welding and embedded in epoxy resin. Then the surfaces of Al-12Si alloy samples were mechanically abrade up to 3000-grit by SiC paper under running water, and polished with suspension containing ceria powder (particle size (d) = 500 nm). In order to observe the microstructure of Al-12Si alloy samples, chemical polishing method was prepared to process the alloy samples. As for chemical polishing method, three-acid-type polishing solution composed of 80% H_3PO_4, 15% H_2SO_4 and 5% HNO_3 (in volume fractions) was freshly prepared [25]. In this process, Al-12Si alloy samples were immersed in the polishing solution at 100 °C for 2.5 min. Then ultrasonic cleaning was applied to treat all alloy samples for 10 min, followed by cleaning in the distilled water lasting for 5 min, finally placed in the drier for 12 h in turn. These as-treated alloy samples were prepared for the electrochemical measurements and microstructural characterization.

2.2. Solution preparation

A 3.5 wt% NaCl solution was prepared for the following weight loss test and the electrochemical measurements. All aforementioned solutions used in this study were in analytical grade reagents and deionized water.

Table 1
Chemical composition (in wt%) of the SLM-produced Al-12Si alloy and as-cast Al-12Si alloy.

Alloy	Al	Si	Fe	Mn	Ti	Zn	C	Ni	Cu	Mg	Sn
Al-12Si(SLM)	Bal.	12.0	0.55	0.35	0.15	0.10	0.05	0.05	0.05	0.05	0.05
Al-12Si (cast)	Bal.	12.0	0.55	0.40	0.15	0.10	0.06	0.05	0.05	0.05	0.05