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Effect of surface roughness on corrosion fatigue performance of AlSi10Mg alloy produced by Selective Laser Melting (SLM)

Avi Leon, Eli Aghion*

Department of Materials Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel

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ABSTRACT

The main interest in Additive Manufacturing technology relates to its ability to produce complex components with relatively reduced weight that are difficult to produce or cannot be produced by other conventional technologies. Although aluminum alloys are considered attractive material for this technology due to their high specific strength and favorable casting characteristics, their surface roughness may have a detrimental effect on their corrosion resistance and corrosion fatigue behavior in particular. The present study aims at evaluating the effect of surface roughness of AlSi10Mg produced by Selective Laser Melting (SLM) followed by stress-relief heat treatment, on the corrosion resistance and corrosion fatigue performance. This was achieved by comparing the corrosion resistance and low cycle corrosion fatigue behavior of SLM samples with their counterpart samples that were polished. The obtained results indicate that the corrosion resistance and corrosion fatigue life span of the SLM samples after polishing were improved compared to that of the unpolished SLM samples. The relatively reduced corrosion resistance and corrosion fatigue endurance of the unpolished SLM samples was related to their increased surface roughness in the form of large amounts of cavities and other surface defects that are inherently produced by the SLM process.

1. Introduction

The growing demand for Additive Manufacturing (AM) components mainly relates to the ability to produce complex structures with thin walls and flexible geometric design [1,2]. Hence this production technology is being considered as an alternative manufacturing method that represents a revolutionary way in which products are designed and manufactured [3]. This technology works in a manner similar to that of traditional laser or inkjet printers. However, in this case, instead of multi-colored inks the 3D printer uses powder that slowly builds an image on a layer-by-layer basis using 3D CAD software [4,5]. Selective Laser Melting (SLM) is considered a promising innovative AM technology that uses high energy intensity laser to fuse fine metal particles into full density solid functional parts [6]. During this process the fabricated material experiences repeated melting and solid state transformation that results in microstructure that is different from the one obtained by conventional processing technologies.

Aluminum alloys are considered very attractive structural materials for AM technology due to their high specific strength [7] and favorable casting characteristics [8,9]. In addition, they have adequate corrosion resistance that is related to their natural ability to form a very stable and adherent passive layer in regular atmospheric conditions. However, it was reported that cast and wrought aluminum alloys are susceptible to pitting corrosion attack in chloride-containing environments [10]. The nucleation of the pitting attack mainly takes place at the interface between the Al matrix and intermetallic phases as well as at defects generated during casting process. In the presence of cyclic loading and corrosive environment the pitting attack sites act as preferred nucleation sites for corrosion fatigue cracking [11]. One of the most popular Al alloys for SLM process that is also being studied by the present research is AlSi10Mg. This alloy offers good strength and hardness and is therefore used for parts with thin walls and complex geometry subjected to high loads, as in the transportation industry [12]. The near-eutectic composition of this alloy according to the Al-Si phase diagram provides sound castability and low shrinkage [13–15]. By now, the effect of SLM process parameters and scan strategies on properties of AlSi10Mg [16–17] is relatively well documented. However, the information in the literature relating to the influence of surface roughness and surface imperfections that may produce a detrimental effect on corrosion resistance and corrosion fatigue performance in particular is quite limited [18–20].

The aim of the present study is to explore the effect of surface roughness on the corrosion resistance and corrosion fatigue behavior of AlSi10Mg produced by SLM process. This is essential in order to

* Corresponding author at: Department of Materials Engineering, Ben-Gurion University of the Negev, PO Box 653, Beer-Sheva 84105, Israel.
E-mail address: egyon@bgu.ac.il (E. Aghion).

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understand the ability of this material system to adequately serve as structural material with predictable properties in service conditions [21].

2. Experimental Procedure

Al alloy specimens with the following composition (in wt%) Al-10.55%Si-0.268%Mg-0.227%Fe-0.004%Mn-0.009%Ti-0.007%Zn-0.004%Cu-0.006%Ni-0.001%Pb-0.001%Sn, as tested by ICP-spectrometer (SPECTRO) were produced by Selective Laser Melting (SLM) technology. The SLM system was EOS EOSINT M 280 equipped with a 400 W Nd-YAG laser and argon as a protective gas atmosphere. The scanning speed was 1000 mm/s, spot size 80 μm, hatch spacing 0.2 mm [22] and layer thickness build-up of 30 μm. The scanning direction was rotated 67° between consecutive layers to obtain optimal densification. The printing orientations of specimens with rectangular and cylindrical shapes were ZX and Z, respectively, according to ISO/ASTM 52921-13 standard. The particle size of the metal powder was 20–65 μm, the particle mean size was 50 μm as measured by QICPIC dynamic image analysis. The effect of surface roughness was evaluated in comparison with SLM specimens that were machined and polished using 1200 grit papers, referred to as "polished" specimens. The surface roughness of the SLM samples in terms of Ra was between 3.2 and 12.5 μm, while that of the polished samples was 0.8 μm. All the SLM samples (unpolished and polished) were subjected to stress-relief heat treatment at 300 °C for 2 h to reduce the inherent hardening effect obtained during the SLM process.

The microstructure was examined by Scanning Electron Microscopy (SEM) using a JEOL JSM-5600 equipped with EDS detector for spot chemical composition analysis. Phase identification was carried out using X-ray diffractometer RIGAKU-2100H with CuKα, 40 KV/30 mA, and a scanning rate of 2°/min. The preferred orientation of the specimens was evaluated using Lotgering's method [23]. The corrosion performance of unpolished and polished specimens was evaluated by immersion test using specimens in horizontal position, and by electrochemical analysis. Both tests were carried out in aerated 3.5% NaCl solution. Corrosion rate measurements were performed according to ASTM G31-12a standard while pitting analysis was evaluated according to ASTM G46 standard. The electrochemical testing included potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) using a Bio-Logic SP-200 potentiostat equipped with Ec-Lab software V10.44 [24,25]. The three-electrode cell used for the electrochemical analysis included a saturated calomel electrode (SCE) as reference electrode, platinum electrode as counter electrode, and the tested specimen as a working electrode with an exposure area of 1 cm^2. The scanning rate of the potentiodynamic polarization analysis was 0.5 mV/s; the EIS measurements were carried out between 100 kHz and 100 mHz at 10 mV amplitude over the open circuit potential. Prior to electrochemical testing, the samples were cleaned in an ultrasonic bath for 5 min, washed with alcohol, and dried in hot air.

The corrosion fatigue performance was evaluated in air and in 3.5% NaCl solution under low cycle fatigue (LCF) conditions using a regular bending machine with a strain control apparatus [26]. The dimensions of the rectangular fatigue specimen were: total length 80 mm, neck length 16 mm, radius of curvature at the neck intersection 15 mm, and thickness 2 mm. The LCF frequency was 0.6 Hz, strain amplitude 3%, and the orientation of the bending stress was vertical to the ZX direction.

3. Results and Discussion

The typical surface texture of unpolished and polished SLM samples is shown in Fig. 1a and b, respectively. This clearly revealed that the texture of the unpolished surface was relatively uneven and contained an excessive amount of cavities and other surface imperfections such as particles with limited bonding to the substrate material. The microstructure at a cross-section of SLM sample obtained after etching is shown in Fig. 1c (XZ plane) and d (XY plane). This exposed the presence of an aluminum matrix containing fine silicon net and selective porosity that was mainly located within the boundaries of the melt pool overlap. It should be pointed out that the relatively deeper melting pools obtained by this study in comparison with the melting pool shown by Manfredi et al. [12] may be related to the differences in the laser power (400 W vs. 200 W in Manfredi's study).

X-ray diffraction analysis presented in Fig. 2 support the assumption that the microstructure was mainly composed of Al/Si phases. In addition, Lotgering calculation method presented in Table 1 revealed that the preferred orientation was (200) plane. This outcome comes in line with the research finding of Thijs et al. that related to the microstructure and texture characteristics of AlSi10Mg produced by SLM process. According to Thijs et al. the SLM process have stimulated epitaxial growth in 〈100〉 direction over the height of the building part mainly due to partial re-melting of the solidification track during SLM process [27].

The corrosion attack at the external surface of the SLM unpolished and polished samples obtained by immersion tests in 3.5% NaCl solution after 15 and 30 days of exposure are shown in Fig. 3. This revealed a relatively more intensive localized corrosion attack at the surface of the unpolished sample that was manifested by multiple sites of pitting and increased corrosion products. The pitting factor and pitting density (pit/cm^2) of the unpolished sample were 23.12 and 2.13, respectively, while those of the polished sample were only 14.2 and 0.93. Typical close-up views at a cross-section of the pitting attack in the two samples illustrating the differences in the morphology of the pits are shown in Fig. 4. While the pits in the polished sample were relatively shallow, the pits in the unpolished sample were much deeper and had a more irregular shape. Hence, it is believed that the internal configuration of the pits in the unpolished sample can comparatively promote the potential of electrolyte stagnation, which consequently can lead to a severe autocatalytic corrosion attack mechanism [28–30]. In addition, the increased surface area of the unpolished sample that acts as cathodic area amplifies the corrosion attack at the pit tip, which acts as anodic region. Altogether it was evident that the localized corrosion attack in the unpolished sample was considerably more intense compared to that of the polished sample, as also illustrated by Fig. 5 in terms of corrosion rate as calculated according to the geometrical size of the two specimens.

Electrochemical characterization by cyclic potentiodynamic polarization analysis of SLM unpolished and polished samples are shown in Fig. 6. This revealed that the corrosion potential of the unpolished alloy was relatively higher − 0.738 V vs. − 0.745 V for the polished sample, while the corrosion current was relatively elevated 0.0035 mA vs. 0.0021 mA. In terms of Tafel extrapolation, the corrosion rate of the unpolished sample was relatively higher compared to the polished sample, 1.57 mpy and 0.95 mpy, respectively. In addition, the cyclic anodic polarization behavior of the two samples revealed that the protection potential (E_{prot}) of the unpolished sample was relatively reduced compared to that of the polished sample. This can be related to the relatively increased difficulties of the unpolished sample to adequately re-passivate [31–33], probably due to the complex morphology and deeper depth of the pitting corrosion attack in this sample. The impedance spectroscopy analysis in terms of impedance modifications after immersion times of 1 and 12 h in 3.5% NaCl solution are shown by Nyquist plots in Fig. 7. Electrical equivalent circuits and related fitted parameters are shown in Fig. 8 and Table 2, respectively. The relatively larger radius of curvature of the Nyquist diagram of the polished sample clearly indicates that its corrosion resistance was relatively improved compared to that of the unpolished sample [34]. The R1 parameter was quite similar in both samples as it represents the solution resistance. The capacitor Q1 and the resistor R2 are related to the double layer and passive film formed on the surface, respectively, while Q2,3, R3, and W3 are associated with the corrosion processes within the pits. The