The improvement of quality index for sand-casting A357 Al-Si alloys by external magnetic fields via Helmholtz coils

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A357 aluminum-silicon alloy is one of the important engineering materials with very high demand in aerospace system, military weapons, and automotive components. Complex and large industrial workpieces cannot be fabricated by machining and forging processes, but only can be formed by casting. Sand casting is low-cost and convenient to mold, but its disadvantage is that castings often suffer from shrinkage cavities, coarsening of grains, and low process yield. The quality index of Al alloy, based on its strength and ductility, can evaluate the quality of aluminum castings so that any parameter affecting the properties of these alloys would also necessarily influence their quality. In the report, mechanical properties and microstructure for sand-casting A357 Al-Si alloy were investigated via an AC magnetic field supplied by low-cost Helmholtz coils. Under the impact of external magnetic fields (0, 6.3, and 10.7 mT), grain refinement of α-Al, reduce of secondary dendritic arm spacing (SDAS), and fibrous structure of eutectic silicon were observed in the microstructure of as-cast A357 alloy. After T6 heat treatment, the eutectic silicon crystal became fragmented and spheroidized; the external magnetic field's agitation caused the eutectic silicon particles' aspect ratio to decrease. Therefore, the magnetic field enhanced the mechanical properties of A357 alloys, including hardness, ultimate tensile strength (UTS), yield strength (YS), and elongation (El). Compared to samples without a magnetic field or with a 10.7 mT field, hardness, UTS, YS, and El increased by 17.9%, 10.6%, 8.8%, and 48%, respectively, with higher magnetic field strengths yielding better sand-cast A357 performance. In conclusion, this cost-effective technique utilizing external magnetic fields enhances the quality index of sand-cast A357 alloys, particularly through α-Al grain refinement and eutectic silicon spheroidization.

Keywords*: A357 Al-Si alloy, magnetic field, sand-cast, Helmholtz coils, T6 heat treatment, eutectic silicon*

1. Introduction

Aluminum-silicon (Al-Si) alloys are widely utilized in aerospace, military, and automotive industries due to their excellent corrosion resistance, lightweight, formability, and comprehensive mechanical properties[1]. Solidification conditions in the casting process significantly impact their microstructures, performance, and quality. Specifically, the surface morphology, α-Al grain size, and eutectic silicon phase morphology profoundly affect Al-Si alloy mechanical properties. Additionally, second dendritic arm spacing (SDAS) in Al-Si alloys influences mechanical behavior significantly, along with intermetallic phases. Unmodified eutectic silicon, porosity, dendrites, and coarse grains can lead to low mechanical properties, necessitating T6 heat treatment for enhancement. Besides T6 heat treatment, grain refiners like Al–Ti–B or element modifiers are commonly used during casting to reduce α-Al grain size and improve eutectic silicon morphology[2]. Application of an external magnetic field during solidification can control convective conditions and influence microstructure formation in cast Al alloys[3]. A low-frequency magnetic field in continuous casting systems reduced macro segregation and solute distribution. Our group introduced magnetic stirring via Helmholtz coils for A357 alloy, successfully enhancement of mechanical properties in sand-casting[4]. Despite its challenges, sand casting remains an attractive option due to its cost-effectiveness and suitability for diverse, large-scale workpieces. In this study, we applied Helmholtz coils to supply an external magnetic field during sand-casting of A357 Al-Si alloy. We investigated the influence of the magnetic field on the microstructures and evaluated mechanical properties of A357 alloy.

2. Experimental

A357 Al-Si alloy with content of Si 7% as raw material was melted at 790°C in a 300 kg crucible using an electrical resistance furnace. Subsequently, inert argon gas was introduced for 5 minutes via a rotary graphite degasser. After degassing, the molten metal was held at 710°C ± 5°C before pouring it into a sand mold at room temperature. To ensure a uniform magnetic field during casting, Helmholtz coils connected to an autotransformer provided magnetic fields of 0, 6.3, and 10.7 mT with an AC voltage of 60 Hz, as measured by a Tesla meter (KANETEC TM-801). For T6 heat treatment, solid solution processing occurred at 540°C ± 2°C for 16 hours, followed by quenching to ambient temperature to create a supersaturated Al-Si alloy. Aging then took place at 160°C for 12 hours.

Metallographic observations focused on both the edge and center of as-cast specimens using an Olympus BX41 optical microscope. Average grain size and SDAS were analyzed using Image-J software. Hardness testing was performed using a Mitutoyo HM-101 Vickers hardness tester with a 1 Kg load, with the average hardness derived from 20 random points on the specimens. Mechanical properties were assessed with a SHIMADZU AG-I 100KN tensile machine employing a strain rate of 1 mm/min. Tensile testing was conducted using a scanning electron microscope (HITACHI S-3400N).

3. Result and Discussion

After sand-casting with magnetic field strengths of 0, 6.3, and 10.7 mT, metallographic analysis reveals the microstructure of A357 ingots, consisting of primary α-Al and eutectic silicon phases. Magnetic field strength and specimen position influenced A357 alloy microstructures, transitioning α-Al grains from columnar dendritic to equiaxed with increasing field strength. Center parts exhibited larger grains due to prolonged solidification. At 100X magnification, metallographic images were used to analyze average grain sizes in sand-cast A357 alloy via Image-J software (Fig. 1). Grain sizes dramatically decreased with magnetic field application, from 203.6 to 106.1 µm at the center. External magnetic fields refined α-Al grains during A357 alloy solidification. The average SDAS values decreasing from 40.2 to 26.3 µm, with reduced standard deviation, as the magnetic field reached 10.7 mT. The external magnetic field during sand casting refined α-Al grains and transformed eutectic silicon into a fibrous structure, driven by Lorentz force-induced forced convection in the melt[5].

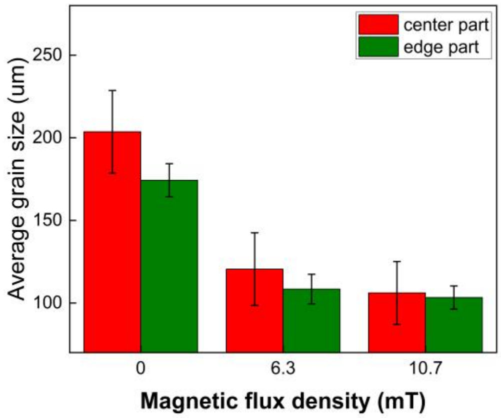

Fig 1. (a) Average grain sizes of A357 alloys casting with different magnetic fields at the center and edge parts of ingots.

Heat treatment improved the uniformity of eutectic silicon distribution by facilitating silicon diffusion into the α-Al matrix, leading to its fragmentation and partial dissolution. resulted in silicon crystal breakdown and spheroidization in Al-Si alloys. Fig 2 show that average hardness of A357 specimens, both as-cast and after T6 heat treatment, increased notably with a 10.7 mT magnetic field. For the as-cast ingot, hardness rose from 66.8 to 74.9 HV, and for the T6-treated one, it increased from 127.3 to 150.2 HV. This enhancement stemmed from the magnetic field's impact on A357 alloy microstructures, which included α-Al grain refinement, SDAS reduction, and eutectic silicon spheroidization.

These alterations increased grain boundary density in smaller α-Al grains and promoted uniform eutectic silicon dispersion in the matrix, hindering dislocation motion and explaining the heightened hardness. Furthermore, the external magnetic field reduced micro-hardness value standard deviation, indicating improved ingot uniformity when using magnetic fields. A tensile test assessed mechanical properties, including ultimate tensile strength (UTS), yield strength (YS), and elongation (El), in as-cast and T6 heat-treated A357 alloys with varying magnetic fields. The UTS and YS values for A357 alloys sand-casted with a 10.7 mT magnetic field increased by 18.5% and 20.3% in as-cast ingots and by 10.6% and 8.8% in T6-treated ingots, respectively.

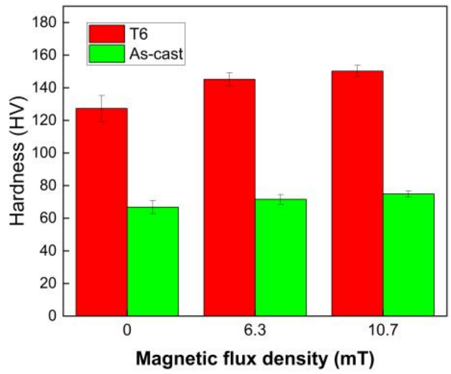

Fig 2. Average hardness for A357 alloy as-cast and after T6 heat treatment at different magnetic fields.

4. Conclusion

This study leading to the following key findings:
1. Magnetic fields during sand casting modified A357 alloy microstructures, refining α-Al grains, reducing SDAS, and spheroidizing eutectic silicon particles.
2. These microstructure modifications by the magnetic field enhanced mechanical properties in both as-cast and T6 heat-treated A357 ingots.
3. Artificial aging treatment further improved A357 alloy strength through precipitation hardening. The combined effects of α-Al grain refinement, uniformity, and eutectic silicon spheroidization induced by magnetic fields played significant roles in enhancing A357 alloy mechanical properties.

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