

Grain Size and Porosity of Silicon Carbide Nanoparticles-Reinforced Aluminum-Silicon Casting Alloys

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Abstract

This letter introduces experimental results on the effects of reinforcement of Al-Si casting alloys with different volumetric percentages of SiC nanoparticles on average grain size and porosity of these alloys. The alloy samples were prepared by conventional casting with mechanical mixing and ultrasonic waves to ensure homogeneous distribution of the nanoparticles. Adding up to 2 vol.% SiC nanoparticles lead to reasonable enhancement in grain crystallization as the average grain size was reduced from 48 μ m for the unreinforced sample to a minimum of 17 μ m. This is attributed to the role of nanoparticles as heterogeneous nucleation sites in the alloy structure. On the other hand, increasing the content of nanoparticles lead to increase the porosity from minimum of 0.5 vol.% to a maximum of 2.6 vol.% at 10 vol.% nanoparticles. This is attributed to the increase in molten viscosity as well as trapped gases during resolidification.

Keywords: Al-Si alloys; Silicon carbide; Nanoparticles; Porosity; Nanocomposites

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1. Introduction

The Al-Si alloys are characterized by the unique balance between their good mechanical properties, low density, high elasticity, and corrosion resistance. Therefore, these metallic systems are among the most employed in automobile and space industry, particularly, in the applications requiring complex structure casting [1-3]. However, its limited surface corrosion resistance and hardness at elevated temperatures represent major challenges that require modification via reinforcing materials [4,5]. In this context, silicon carbide (SiC) nanoparticles are proposed as an ideal reinforcing material due to their super-hardness, high thermal stability, and relative chemical compatibility with aluminum matrix [6,7]. Research studies have shown that the addition of SiC nanoparticles can reasonably enhance the mechanical properties of the alloys but such enhancement is tightly related to the capability of the manufacturing process to control two crucial parameters: grain size and porosity [8-10]. SiC nanoparticles act as heterogeneous nucleation sites during resolidification, which leads to refine the microscale grains and reduce their size. This refinement – in turn – causes to enhance the hardness and toughness according to the Hall-Petch relationship [11]. On the other hand, due to the high specific surface area and activation energy, these nanoparticles naturally tend to agglomerate and hence increase the viscosity of the molten, trap gases such as hydrogen, or create

shrinkage voids during resolidification, and consequently increase the porosity [12-14].

Porosity is the most harmful structural defect in solids because it concentrates the stresses, reduces the density and thermal conductivity, and hence initiate cracks. Therefore, the aim of this letter is to introduce the interaction between grain size and developing porosity in Al-Si alloys reinforced with different percentage volumetric ratios of SiC nanoparticles in order to determine optimum parameters such as reinforcing ratio, cooling rate, and mechanical treatment, those allow maximum grain refinement as well as minimum increase in porosity during the manufacturing of hybrid materials with lightweight and high performance [15-18].

2. Experimental Part

The Al-Si alloys (type A356) were prepared by conventional casting as the fundamental alloy was initially melted in a graphite pot inside an electrical resistance furnace at 750°C. to ensure uniform distribution of SiC nanoparticles of 50nm average size, different amounts of these nanoparticles (vol.%) were added to the molten as the main variable while a reference sample (0 vol.% SiC) was kept. To overcome the problem of nanoparticles agglomeration due to van der Waals forces, the double-feeding method was used by mechanical stirring at 300 cycles/min for 15 minutes followed by treatment with 1kW ultrasonic waves for 10 minutes

to prevent agglomeration. The homogeneous molten was then poured into metallic molds previously heated at 250°C to allow uniform cooling.

In order to study the effects of volumetric percentage of SiC nanoparticles on the grain size within the alloy, samples were polished to develop the grain boundaries using appropriate chemical solutions. The grain size was estimated using ImageJ software according to ASTM E112 standard. For porosity measurements, the apparent density of the samples were calculated by Archimedes method and compared to the theoretical density calculated by mixing rule. The surface morphology was introduced by optical microscopy to determine the shape and distribution of the resulted pores.

3. Results and Discussion

The optical microscope images of the A356 alloy samples in Fig. (1) show apparent difference in the microstructures of unreinforced and reinforced alloys. The unreinforced sample shows a clear and large-size dendritic structure with primary and secondary extended branches, while the reinforced sample shows a major transformation into grain refined structure, which is attributed to the role of SiC nanoparticles as heterogeneous nucleation centers during the resolidification of the melted alloy. This hinders the growth of dendritic branches and leads to noticeable reduction in the grain size. Furthermore, the distribution of nanoparticles shows a positive effect in decreasing the porosity of the alloy throughout filling the space between grains and modifying the flow pattern of the molten, which results in higher density for the reinforced alloy and better distribution of the phases when compared to the reinforced alloy in which the inter-grain voids appear much more apparent. This enhances the final mechanical properties of the produced nanocomposites.

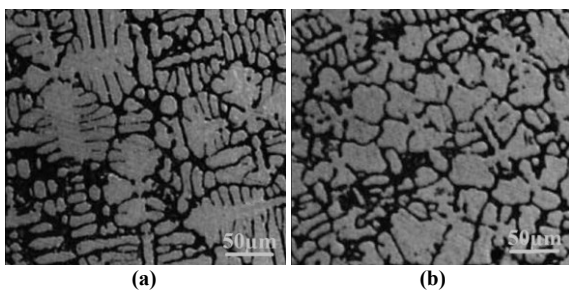


Fig. (1) Optical photomicrographs: (a) unreinforced A356 alloy (b) A356 reinforced with 1.5 vol. % SiC

Figure (2) shows the variation of average grain size with the volumetric percentage of SiC nanoparticles added to the Al-Si alloy. In the unreinforced sample (0 vol.%), the average grain size was about 48µm, which is the maximum value. As the SiC nanoparticles were added at 0.5 vol.%, the

average grain size was sharply decreased to 25µm due to the role of nanoparticles as heterogeneous nucleation sites. The average grain size continued to decrease with increasing the content of nanoparticles to reach 17µm at 2 vol.%. Interestingly, the continuous increasing nanoparticles content did not cause any further decrease in the average grain size, i.e., no further enhancement in grain refinement was observed. This stability is possibly interpreted by reaching the maximum number of active nanoparticles as nucleation sites those can be found in the metallic matrix. The excess content lead to agglomeration and hence the particles lose their ability to reduce the grain growth.

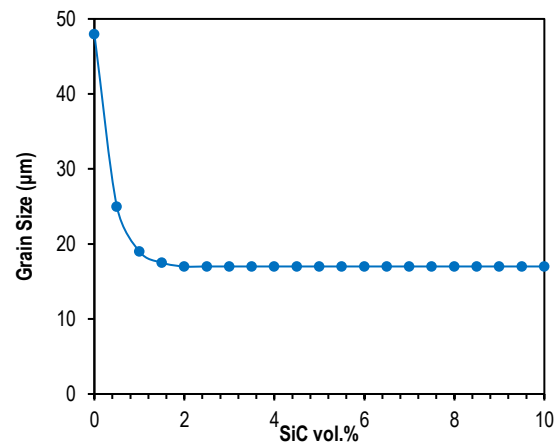


Fig. (2) Variation of average grain size of Al-Si alloy reinforced with SiC nanoparticles at different volumetric content

Figure (3) shows the variation of percentage volumetric porosity with the volumetric percentage of SiC nanoparticles added to the Al-Si alloy. The unreinforced sample (0 vol.%) showed the minimum porosity (~0.5 vol.%), which represents the natural level of trapped gases and shrinkage in conventionally-casted alloys.

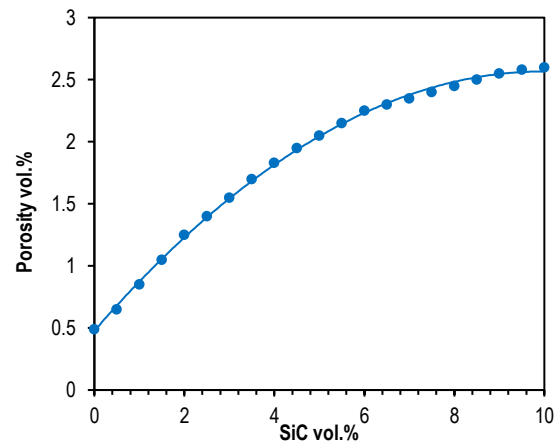


Fig. (3) Variation of porosity as a volumetric percentage of Al-Si alloy reinforced with SiC nanoparticles at different volumetric content

As the nanoparticles were slightly added to the alloy (0.5 vol.%), the porosity was slightly increased to 0.65 vol.%, which refers to the initial effect of nanoparticles to hinder the metallic flow during resolidification. The porosity was gradually increased with continuous increase in the nanoparticles content, which is expected behavior due to increasing viscosity of the molten as a result of adding nanoparticles. The porosity reached its maximum of about 2.6 vol.% at nanoparticles content of 10 vol.%. It is apparent that the curve did not show stability as the higher content of nanoparticles mostly lead to agglomerate, trap gases, and finally hinder the liquid metal feeding within the dendritic branches during resolidification.

4. Conclusion

In conclusion, adding SiC nanoparticles to the A356 alloy reasonably enhances the grain crystallization and reduces grain size. The excess content of nanoparticles in the alloy does not cause further enhancement in the crystallization and porosity of the alloy due to the agglomeration and inactivity of the nanoparticles. Accordingly, the optimum content of SiC nanoparticles in Al-Si alloy lies at low values (~2 vol.%) as a balance between grain size and porosity is achieved with accurate control of mixing and cooling processes.

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