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Analysis of Mechanical and Physical Properties of Al-Si (Al-Si) Casting Alloys Reinforced with Various Eggshell Nanopowders

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Abstract. Al-Si alloy was synthesized of combining aluminum and silicon (Al-Si). The addition of 15% silicon was aimed to improve the ductility and hardness of aluminum up to 525 MPa. It was also intended for reducing defects from gas porosity. However, the use of more than 15% silicon would make the alloy more brittle drastically which microscopically representing by the formation of crystalline silica granules. This study involved eggshell nanopowders as reinforcing material in enhancing hardness and ductility of Al-Si alloy. The casting process began with synthesizing eggshells into nanopowders. We added a certain amount of eggshell nanopowders (ESNPs) (0.05%, 0.1%, or 0.2%) into the Al-Si molten and subsequently mixed using a stirrer for 1 minute. The resulting mixture was poured into a permanent mold. It was shown that the Al-Si casting reinforced with 0.1% ESNPs had the highest tensile strength of 20.38 kg/mm² and the highest hardness of 137.9 HV. Further analysis revealed that the microstructure homogeneity of the samples is strongly affected its hardness.

Keywords: Al-Si, alloys, eggshell nanopowders, hardness, microstructure

1. Introduction

In general, the production of castings out of various types of metals involves several steps: melting the metal, pouring the molten metal into a mold, and cooling the casting using various cooling media, one of which is air cooling. The casting process was first performed when people began to understand how to melt metal and make a mold [1]. One of the most commonly used metals in casting is aluminum, particularly its alloys. An aluminum alloy is a blend of pure aluminum and silicone as the major alloying element which serves to improve the properties of aluminum due to its good castability; Al-Si based casting alloys to constitute approximately 90% of total aluminum castings [2]. Al-Si (Al-Si) alloys are widely used in the automotive industry, especially the manufacture of pistons, due to their excellent wear and corrosion resistance, low thermal expansion coefficients, and high strength and weight ratio [3,4].



Eggshell waste is produced in large quantity by hatcheries, households, restaurants, bakeries, and food processing companies [5]. The main compositions of eggshell nanopowder are carbonate, sulfate, calcium, magnesium phosphate, and organic materials. The elements of Na, K, Mn, Fe, Cu, Sr are also found in eggshell [6]. The density of eggshell is about 2.53 g/cm^3 . An eggshell is composed of 94% calcium carbonate, 4% organic matter, 1% calcium phosphate, and 1% magnesium carbonate, as well as smaller amounts of inorganic components such as Ca, Mg, Si, and Zn [7–9].

It was reported that eggshells show relatively lower density than calcium carbonate potential as a great source of filler in polymer composites [10]. Over the past few years, efforts have been conducted to utilize eggshells in the manufacturing of biodiesel and collagen, but the result is not economically efficient [11]. Furthermore, eggshells can be processed into other useful materials such as fertilizers, building materials, and powder for metal and polymer reinforcement in composite development [12].

Mechanical properties refer to properties possessed by material in response to external pressure. Such properties include tensile, compressive, flexural and torsional strength, hardness, brittleness, resilience, and toughness. Prior to using a material for a specific purpose, its properties should be identified by conducting mechanical testing such as tensile test with extensometer, impact test using the universal testing machine, and hardness test. These tests require standardized sample preparation [13,14].

Previous research has attempted to improve the mechanical properties of Al-Si alloys by adding eggshell nanopowder. It was shown that the addition of composites resulted in favorable impacts on mechanical properties, i.e., improved tensile strength, elastic modulus, hardness, toughness, impact resistance, and compressive strength. In other words, eggshell nanopowder can serve as an effective reinforcing material [15]. The use of eggshell nanopowder has been proven to be effective for the reinforcement of aluminum alloys for casting, hence lowering the melting point of aluminum alloys [16]. So far it is rarely found the comprehensive report on the study of the addition of eggshell nanopowder (ESNPs) in Al-Si alloy associated with their microstructure and mechanical properties. We report the eggshell nanopowders, synthesize of x(ESNPs)-Al-Si on microscopically from micro- and macrographs analysis as well as their mechanical properties.

2. Methods

Three samples with different amount of ESNPs, i.e., 0.05%, 0.1%, and 0.2% were added to Al-Si alloy. As the initial step of the experiment, eggshell specimens were prepared by natural sun drying and grinding for 5 hours using a ball mill up to 500 mL capacity f (MTI Corporation). The next step was the preparation of the casting material, i.e., motorcycle scrap pistons. Scrap piston was put in furnace for 3 hours to be melted, producing 1.5 kg molten aluminum. The ESNPs poured into molten aluminum and mixed for 1 minute by using stirrer (Bosch). Then, the mixture poured into a cylindrical mold with a size of 16 cm in length and 1.4 cm in diameter and then cooled by using air media for 24 hours. The following step was turning or forming the Al-Si casting using metal lathe (Magnum Tech FEL-1640 GCY) to obtain a standard specimen for the tensile test. The specimens were ready for the mechanical test using the universal testing machine (UTM) of Tokyo Testing Machine MFG, the microstructure of Al-Si casting was observed by using a metal microscope (Nikon), macrostructure of Al-Si casting was taken by using camera (Canon), and hardness test conducted using Rockwell hardness tester (CV 600A).

3. Results and Discussion

3.1. Tensile test

The tensile test aimed to obtain tensile strength data, in which tensile loading was subjected into specimens until fracture occurred [1]. Tensile test was conducted according to the ASTM A370-16 standard [17]. Figure 1 shows the tensile strength of three Al-Si specimens which reinforced by using ESNPs with the percentage of 0.05%, 0.1%, and 0.2%. It is readily seen that the specimen contained 0.1% eggshell had the highest tensile strength, i.e., 20.38 kg/mm^2 . The other Al-Si specimens which contained 0.05% and 0.2% eggshell sequentially had a tensile strength of 12.24 kg/mm^2 and 16.86 kg/mm^2 . The results indicated that tensile strength decreased when the amount of reinforcing material was increased to 0.2%. This study revealed that the use of 0.1% and 0.2% eggshell resulted in higher

tensile strength than Al_2O_3 , TiO_2 , and Al_2O_3 nanoparticles [18]. The results of the two studies are presented in Table 1.

Table 1 shows the tensile strength comparison of Al-Si alloy that reinforced using several reinforce materials. Table 1 shows that the use of ESNPs as reinforcing material yields the greater tensile strength of Al-Si alloy than the use of Al_2O_3 , TiO_2 , and Al_2O_3 . Of one of the specimens reinforced with a small amount of eggshell, the tensile strength exceeded specimen which reinforced using Al_2O_3 , TiO_2 , and Al_2O_3 [18].

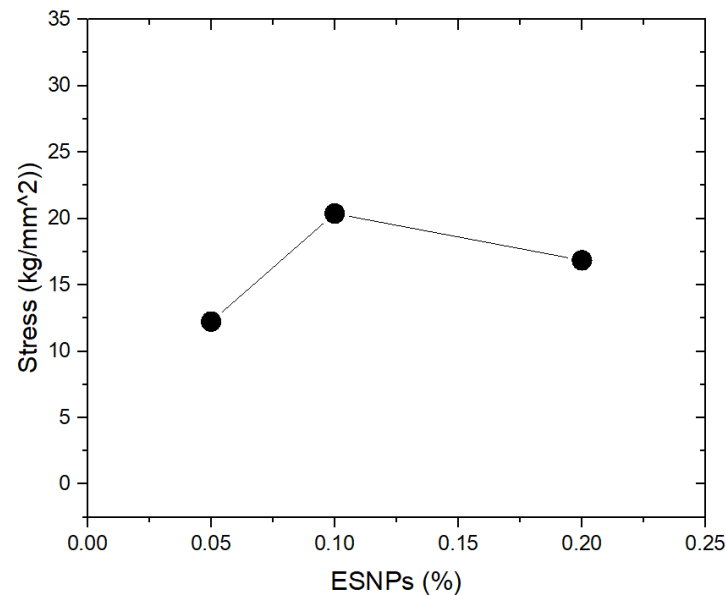


Figure 1. Tensile test on Al-Si reinforced by using ESNPs with the percentage of 0.05%, 0.1%, and 0.2%.

Table 1. Tensile Strength Comparison of Al-Si Alloy Containing Different Reinforcing Material

No.	Reinforcing Material	Tensile Strength (kg/mm ²)	References
1	0.05% Eggshell	12.24	[18]
2	0.1% Eggshell	20.38	
3	0.2% Eggshell	16.86	
4	0% Al_2O_3	15.8	
5	1% Al_2O_3	17.3	
6	2% Al_2O_3	19.8	
7	4% Al_2O_3	16.6	
8	0% TiO_2	15.8	
9	1% TiO_2	16.1	
10	2% TiO_2	16.7	
11	3% TiO_2	18.8	
12	5% TiO_2	16.6	
13	0% ZrO_2	15.8	
14	1% ZrO_2	16.3	
15	2% ZrO_2	17	
16	3% ZrO_2	18.1	
17	5% ZrO_2	16.7	

3.2. Hardness test

The results of hardness measurement are shown in Figure 2.

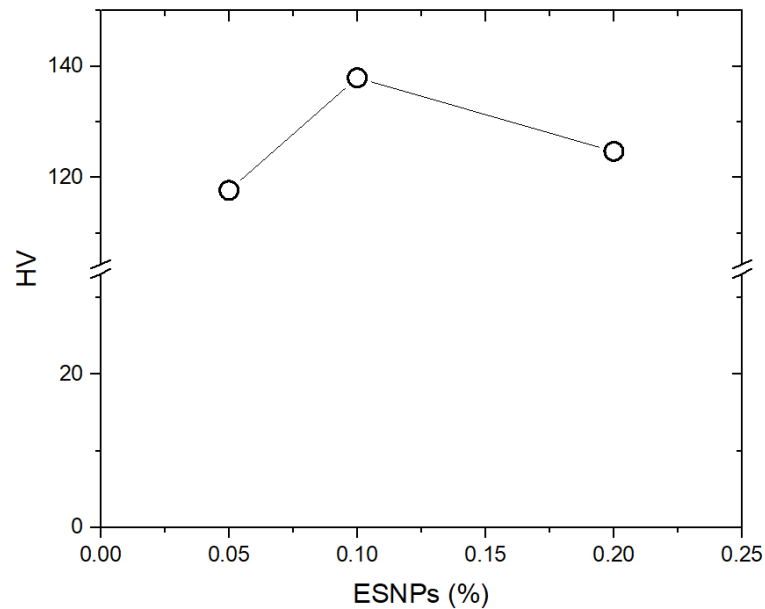


Figure 2. Hardness HV on Al-Si castings reinforced as a function of eggshell NPs.

Table 2. Comparison of Hardness Values of Al-Si Specimens Containing Different Reinforcing Materials

No.	Reinforcing Material	Hardness (HV)	Reference
1	0.05% Eggshell	117.7	[19]
2	0.1% Eggshell	137.9	
3	0.2% Eggshell	124.7	
4	Without Zinc Oxide Nanorods	78.3	
5	0.05% Zinc Oxide Nanorods	78.6	[18]
6	0.1% Zinc Oxide Nanorods	79.2	
7	0.2% Zinc Oxide Nanorods	80.6	
8	0% Al ₂ O ₃	103	
9	1% Al ₂ O ₃	108	
10	2% Al ₂ O ₃	130	
11	4% Al ₂ O ₃	132	
12	0% TiO ₂	103	
13	1% TiO ₂	114	
14	2% TiO ₂	130	
15	3% TiO ₂	141	
16	5% TiO ₂	92	
17	0% ZrO ₂	103	
18	1% ZrO ₂	116	
19	2% ZrO ₂	137	
20	3% ZrO ₂	147	
21	5% ZrO ₂	101	

The results showed that specimen which reinforced by using 0.1% of ESNPs had the higher hardness value than the other specimen which reinforced by using 0.05% and 0.2% of ESNPs. The reinforcement of Al-Si alloy by using 0.05%, 0.1%, and 0.2% of ESNPs had a hardness value of 117.7 HV, 137.9 HV, and 124.7 HV, sequentially. While the highest tensile strength and hardness value had achieved by using 0.1% of ESNPs. This work with the reinforcement by using ESNPs of 0.05%, 0.1%, and 0.2% had the higher hardness compared to the others [19] and [18]. The specimens reinforced with zinc oxide nanorods had a lower hardness than those with eggshell nanopowder. The addition of Al_2O_3 , TiO_2 , and Al_2O_3 resulted in castings with higher hardness than ESNPs, but the percentage of Al_2O_3 , TiO_2 , and Al_2O_3 used was 5-20 times higher than that of eggshell nanopowder. In more detail, the comparison is shown in Table 2.

3.3. Macrostructure observation

The macrostructure of specimens was captured to analyze the fracture in the specimen after tensile test. This analyzes aimed to observe closely the Al-Si alloy properties which reinforced with different amounts of ESNPs (0.05%, 0.1%, and 0.2%). The macrostructure showed the distribution of Al-Si particle size in specimens, clearly. Mechanical properties of Al-Si alloy was affected by morphology, distribution, and size of the particle [20].

The macro images of the three specimens show a significant difference in fracture behavior. As shown in Figure 3a, brittle fracture occurred since a mixture of cleavage, and fibrous fracture appeared; the pieces could fit back together, had a shiny, highly reflective surface [18–20], but dull in some parts. Figure 3b shows a flat fibrous fracture with a dimpled, light-absorptive, and dull surface, and the pieces could not be fitted back together. Figure 3c shows the appearance of a mixed mode fracture with an uneven surface, a hole in the middle, and other characteristics of a mixed mode fracture. It is evident that the addition of 0.1% eggshell nanopowder could produce quality castings with high hardness and a fine-grained structure.

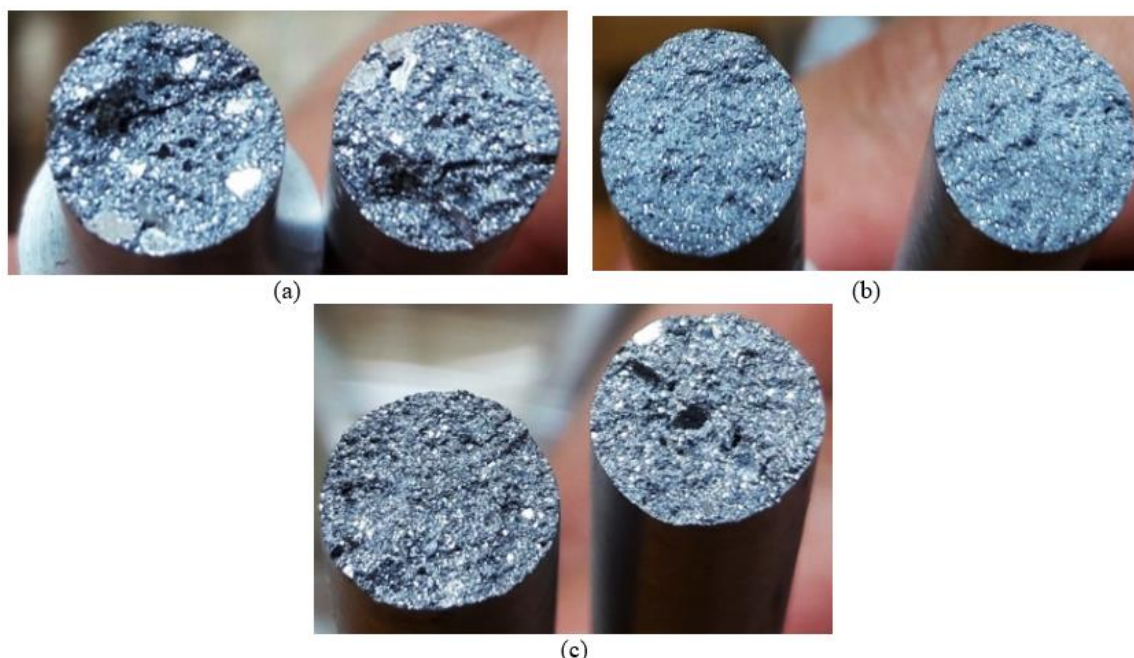


Figure 3. Macro photographs of Al-Si specimens reinforced with (a) 0.05, (b) 0.1, and (c) 0.2% ESNPs.

3.4. Microstructure Observation

Microstructure observation was performed at the Mechanical Engineering laboratory of Universitas Merdeka Malang. The polishing and etching of specimens were observed closely using a microscope with 881x magnification. The photomicrographs of all variations are shown as follows.

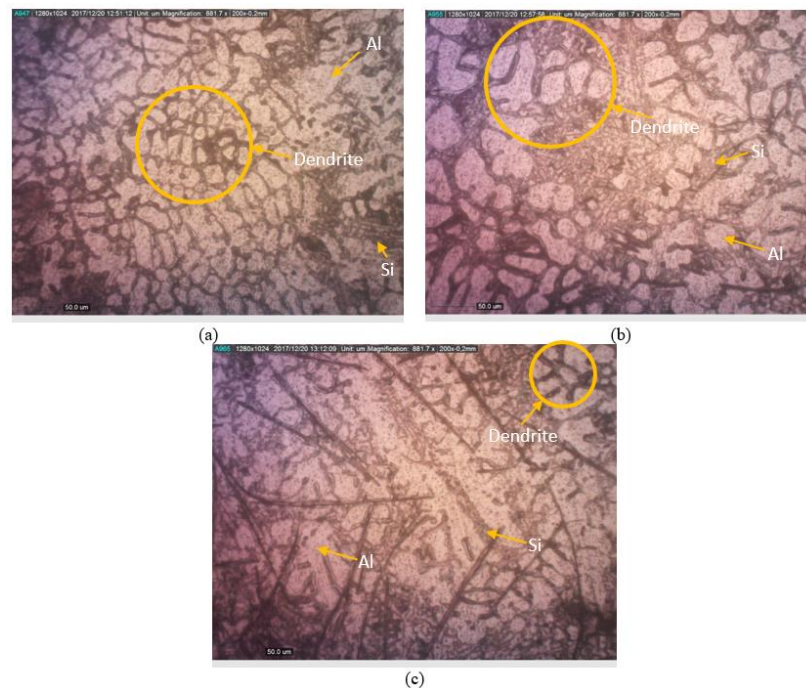


Figure 4. Photomicrographs of Al-Si specimens reinforced with (a) 0.05, (b) 0.1, and (c) 0.2% ESNPs.

As shown in Figure 4, the microstructure of each casting reinforced with eggshell was different considerably. Figure 4a shows a uniform grain size distribution and nearly the same dendrites (as circled in yellow). Figure 4b shows a relatively even grain size distribution and bigger grain size than that in Figure 4a. Larger dendrites also appeared. In contrast, Figure 4c shows an uneven grain structure and the biggest dendritic structures when compared to the specimens reinforced with 0.05% and 0.1% eggshell nanopowder [16,18,19]. The results suggest that materials with a dense and small grain structure could have high ductility, impact resistance, and density, but low porosity.

4. Conclusion

We may conclude that the Al-Si casting reinforced with 0.1% eggshell nanopowder exhibits the highest tensile strength of 20.38 kg/mm² and the highest hardness value of 137.9 HV. Macro photography and micrographs observations support these results. It was shown that the use of 0.1% eggshell as a reinforcement yielded a denser and smaller grain size. The homogenous distribution also affects mechanical properties.

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