Mechanical and physical properties of aluminium-silicon (Al-Si) casting alloys reinforced by Zinc Oxide (ZnO)

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Abstract. This study aimed to enhance the properties of aluminium-silicon (Al-Si) alloys by adding zinc oxide as a reinforcing material. This study was a type of pre-experimental design called the one-shot case study, in which sample groups subjects were given treatments and then observed. The steps included melting the aluminium-silicon in a furnace at 900° C, adding a certain amount of zinc oxide (0.05%, 0.1%, or 0.2%), stirring the mixture for 1 minute, and pouring it into a permanent mould. Results showed that, among the three specimens, the specimen reinforced with 0.2% zinc oxide had the highest tensile strength of 23.9 kg/mm², the greatest hardness of 134.4 HV, and a flat surface with evenly distributed grains and more brittle fracture.

1 Introduction

The process of metal casting includes melting the metal, pouring it into a mould, and letting it cool and solidify [1]. Aluminium-silicon casting alloys are widely used in automotive and aircraft industries because of their excellent properties such as low density, high strength-to-weight ratio, high corrosion resistance, good impact resistance, good thermal conductivity, and high wear resistance [2]. The addition of certain elements, such as calcium, sodium, strontium, and antimony, to aluminium-silicon alloys gives a fine eutectic structure or finer fibrous form [3].

Zinc oxide (ZnO) is a white powder that is insoluble in water. It is frequently used as an additive in various materials and products including rubbers, plastics, ceramics, glass, cement, lubricants, paints, ointments, adhesives, pigments, foods, batteries, and fire retardants; its utilisation as a casting material is still uncommon. Zinc oxide (ZnO) is a

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unique material that has semiconducting, piezoelectric, and pyroelectric properties. When employing a solid-vapour thermal sublimation method, nanocombs, nanorings, nanohelices/nanosprings, nanobows, nanobelts, nanowires, and nanocages of ZnO have been synthesised under specific growth conditions. These unique nanostructures clearly show that, among all materials, ZnO presumably has the richest family of nanostructures, both in structures and properties [4]. Physically, ZnO occurs as a white powder and is referred to as zinc white. Zinc oxide is an amphoteric oxide and nearly insoluble in water and alcohol but easily soluble in acids. The mineral form of zinc oxide is red or yellow, not the usual white colour, because it contains impurities such as manganese (Mn) and other elements. The crystalline form of zinc oxide crystals is thermochromic, which makes the colour change from white to yellow when heated and vice versa when cooled [5]. Improved casting properties of Al-Si alloys are achieved by melting nano-sized particles [6]–[11].

The mechanical properties can be enhanced by controlling additional materials, alloying elements, compaction rates, heat treatment, and others [12]. Jabeera et al. [13] explained the effects of zinc oxide nanoparticles on the aluminium-zinc alloy anodes. They found that ZnO nanoparticles could activate the sacrificial anodes effectively and were suitable for reinforcing aluminium alloy anodes. The substantial improvement of the metallurgical properties of anodes occurred due to reinforcing the anodes with nanoparticles, resulting in a significant reduction in the value of self-corrosion. Shin et al. [14] studied the refining effect of aluminium alloy (A356) microstructures by conducting an exothermic chemical reaction called aluminothermic reaction on aluminium alloy (A356) and zinc oxide nanoparticles (ZnO, ~20 nm in size) and the results showed an improvement in mechanical properties. Qasim et al. [2] studied the effect of adding zinc oxide nanorods to aluminium casting and found that it improved the mechanical properties.

2 Method

This study was pre-experimental research involving sample groups given treatments and then observed. In this research, the addition of a different percentage of zinc oxide (0.05%, 0.1%, and 0.2%) to Al-Si as the base material was observed. The cast specimens composed of Al-Si and varying amounts of zinc oxide were analysed by tensile testing using a machine from Tokyo Testing Machine MFG, hardness testing using a Rockwell type hardness tester (CV 600A), and morphological observation using a metal microscope from Nikon and a camera for macro photography from Canon.

As the initial step of the experiment, scrap pistons as the primary casting material and zinc oxide as the reinforcing agent were prepared. The scrap pistons were melted in a furnace for about 3 hours, producing 1.5 kg molten aluminium. Zinc oxide was then added to the molten aluminium and mixed using a stirrer from Bosch [15]. The resulting mixture was poured into a permanent mould and then air-cooled. The next stage was shaping the casting pieces using a metal lathe (Magnum Tech FEL-1640 GCY) to obtain standard tensile test specimens [16]. Macro photographs of the specimens subjected to tensile testing were taken for fracture analysis. After tensile testing, the specimens were cut for hardness testing.

3 Results and Discussion

3.1 Tensile Testing

The tensile strength of a material can be determined by conducting a tensile test. The tensile testing also aims to identify other properties such as creep strength, elongation, cross-

section reduction, and modulus of elasticity. During tensile testing, specimens were subjected to tensile loading until fracture occurred [1]. The test was performed based on the ASTM A370-16 standard [16]. The test results are presented in Figure 1

Fig. 1. Tensile strength of Al-Si castings reinforced with 0.05%, 0.1% and 0.2% zinc oxide

Figure 1 shows the improved tensile strengths of three aluminium silicon specimens reinforced with 0.05%, 0.1% and 0.2% zinc oxide. The Al-Si cast alloy reinforced with 0.1%, 0.05%, and 0.2% zinc oxide had a tensile strength of 14.052 kg/mm², 19.25 kg/mm², and 23.9 kg/mm², respectively. These results showed that the more the amount of zinc oxide, the higher the tensile strength.

Table 1. Comparison of the Tensile Strength of Al-Si Specimens Reinforced with Different Materials

No.	Reinforcement	Test Result	Reference
		Tensile Strength (kg/mm²)	
1	0.05% Zinc Oxide	14.052	
2	0.1% Zinc Oxide	19.25	
3	0.2% Zinc Oxide	23.9	
4	0.05% Eggshell	12.24	Rizkiyan A (2018)
5	0.1% Eggshell	20.38	
6	0.2% Eggshell	16.86	
7	0% Al ₂ O ₃	15.8	Iman S et al. (2015)
8	1% Al ₂ O ₃	17.3	
9	2% Al ₂ O ₃	19.8	
10	4% Al ₂ O ₃	16.6	
11	0% TiO ₂	15.8	
12	1% TiO ₂	16.1	
13	2% TiO ₂	16.7	
14	3% TiO ₂	18.8	
15	5% TiO ₂	16.6	
16	0% ZrO ₂	15.8	
17	1% ZrO ₂	16.3	
18	2% ZrO ₂	17	
19	3% ZrO ₂	18.1	
20	5% ZrO ₂	16.7	

As shown in Table 1, the addition of zinc oxide as a reinforcement could result in greater tensile strength than the use of Al₂O₃, TiO₂ and ZrO₂ nanoparticles. Though smaller

in amount, zinc oxide could generate castings with a tensile strength exceeding the specimens reinforced with Al_2O_3 , TiO_2 and ZrO_2 nanoparticles [7]. Compared to the use of 0.05%, 0.1%, 0.2% eggshell [17], still the addition of 0.2% zinc oxide could produce a higher tensile strength.

3.2 Hardness Testing

A three-point test was performed on each specimen. The results of hardness testing are shown in Figure 2.

Fig. 2. Hardness of Al-Si castings reinforced with 0.05%, 0.1% and 0.2% zinc oxide

The results showed a notable difference in the hardness value of the three specimens (reinforced with 0.1%, 0.05%, and 0.2% zinc oxide). The addition of 0.05%, 0.1%, and 0.2% zinc oxide resulted in a casting product with a hardness value of 126.3 HV, 129.7 HV, and 134.4 HV, respectively. In other words, the more the amount of zinc oxide, the higher the hardness value.

Table 2. Comparison of the Hardness of Al-Si Specimens Reinforced with Different Materials

No.	Reinforcement	Test Result	Reference
		Hardness (HV)	
1	0.05% Zinc Oxide	126.3	Qasim et al. (2017)
2	0.1% Zinc Oxide	129.7	
3	0.2% Zinc Oxide	134.4	
4	Without Zinc Oxide Nanorods	78.3	
5	0.05% Zinc Oxide Nanorods	78.6	
6	0.1% Zinc Oxide Nanorods	79.2	
7	0.2% Zinc Oxide Nanorods	80.6	
8	0% Al_2O_3	103	Iman S et al. (2015)
9	1% Al_2O_3	108	
10	2% Al_2O_3	130	
11	4% Al_2O_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	

Table 2 shows that the specimens reinforced with 0.05%, 0.1%, and 0.2% zinc powder had greater hardness values than those in the research conducted by Qasim et al. [2] and Iman S et al. [7]. The addition of Al_2O_3 , TiO_2 and ZrO_2 generated more hardness but the amount of it was 5-20 times more than zinc oxide.

3.3 Microstructure Observation

Microstructure observation was performed at 881.7x magnification. Prior to observation, the specimens were polished and etched in accordance with ASTM E407-99 standard [18]. The observation aimed to examine the particle size distribution of Al-Si specimens. The size, morphology, and distribution of microstructures affect mechanical properties [19]. The observed results show a uniform distribution of particles in Al-Si alloys. The photomicrographs of specimens reinforced with varying amounts of zinc oxide are presented in Figure 3a-c.

Fig. 3. Photomicrographs of tensile fracture surface: (a) Al-Si reinforced with 0.05% zinc oxide, (b) Al-Si reinforced with 0.1% zinc oxide, and (c) Al-Si reinforced with 0.2% zinc oxide

The microstructure of specimen reinforced with 0.05%, 0.1%, and 0.2% zinc oxide is shown in Figure 3a, 3b, and 3c, respectively. Figure 3a shows a uniform grain size distribution with some dendrites [2], [7], [10]. Compared to Figure 3a, Figure 3b shows a smaller grain size but larger dendrite size; solidification occurred much faster in this specimen [2], [7], [10]. Figure 3c shows that the grains become smaller and denser, grain

boundaries are more clearly visible, and the dendrite structure is smaller, and grains are distributed more evenly than the other specimens [2], [7], [10]

3.4 Macrostructure Observation

The results of tensile testing were captured up close using a macro photography camera.

Fig. 4. Macro photographs of tensile fracture surface: (a) Al-Si reinforced with 0.05% zinc oxide, (b) Al-Si reinforced with 0.1% zinc oxide, and (c) Al-Si reinforced with 0.2% zinc oxide

Figure 4a shows a brittle fracture, i.e. a shiny, reflective, and flat surface [2], [7], [20], [21]. Figure 4b shows a more brittle fracture, namely a flat surface that reflects light sharply and with no deformation during tensile testing; it occurred due to an increase in the hardness of casting material [2], [7], [20], [21]. Figure 4c shows the appearance of a more brittle fracture and an increase in tensile strength, compared to the other specimens; it shows a flat, highly reflective surface with no deformation as well as a material with high hardness and a fine-grained structure [2], [7], [20], [21].

4 Conclusion

The research results about Al-Si alloys reinforced with 0.05%, 0.01% and 0.2% zinc oxide have led to the following conclusions. Among the three specimens, the Al-Si casting reinforced with 0.2% zinc oxide had the highest tensile strength of 23.9 kg/mm² and the greatest hardness of 134.4 HV. This is supported by the macro image showing that the grains are smaller and denser, grain boundaries are more clearly visible, the dendrite structure is smaller, and grains are distributed more evenly than the other specimens; the smaller and denser the grains, the higher the ductility and strength. Photomicrography also showed that the addition of 0.2% zinc oxide resulted in a cast with a significant increase in tensile strength and more brittle fracture than those with the other concentrations; the image shows a flat, highly reflective surface with no deformation as well as a material with high hardness and a fine-grained structure.

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