MICROSTRUCTURE DEVELOPMENT AND TENSILE PROPERTIES OF ADC12 AL-SI ALLOY WITH DIFFERENT CONTENT OF PRASEODYMIUM (PR)

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Abstract. Vehicle weight reduction is very important due to economic and environmental needs. To this end, the automotive and aerospace industries use aluminum cast alloys extensively. The needle-like/flake-like eutectic silicon in the cast structure decreases percentage of elongation, fracture toughness, and fatigue resistance. Therefore, casting units use eutectic silicon modification extensively on molten aluminum-silicon alloys to transform flake-like silicon to fibrous silicon, improving its properties. Hence, the current research aims to investigate the effect of praseodymium (Pr) addition on the microstructure changes and the tensile properties of the ADC12 Al-Si alloys. The ADC12 Al-Si alloy with different percentages of Pr (0.1, 0.3, 0.5, and 1.0 wt. %) were prepared by gravity casting technique. The microstructural analysis and tensile properties were conducted using an optical microscope (OM), scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) analysis and tensile test. The results showed that ADC12 Al-Si alloy treated with 0.5 wt. % of Pr demonstrates the lowest grain size and aspect ratio composition as well as highest tensile results compared to other fabricated alloys. The eutectic Si grain size decreases at 0.5 wt. % Pr where the value of aspect ratio is the lowest. There is an increment in ultimate tensile strength (UTS) and elongation by 20.05 % and 40.35 %, respectively, with the addition of 0.5 wt. % Pr.

Keywords: ADC12 Al-Si alloy, Pr addition, refinement, microstructure, mechanical properties

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Introduction

Aluminium (Al) is one of the common elements used widely in manufacturing and our daily lives, as described by Zamani et al. [1]. Besides that, aluminium also has unique characteristics that lead others to use it in most products nowadays. For example, Ye et al. [2] claimed that aluminium has low strength and hardness compared to other metals such as steel (Fe), brass (CuPbZn), copper (Cu), zinc (Zn), lead (Pb), and titanium (Ti). Still, it has some similarities based on physical, chemical and mechanical characteristics. Other than that, the Al alloy is also known for its good properties such as strength to weight ratio, corrosion resistance, electrical and thermal conductivity, light and heat reflectivity, and toxicity [3]. Silicon (Si) uses as an alloying element for Al. The addition of Si helps reduce the manufacturing cost, gives an excellent castability, higher specific strength, and recycling [4]. ADC12 Al-Si alloy is also one of the Al-Si alloy types consisting of Si, Mg, Fe, Zn, and Mn within the composition, as stated by Indarsari et al. [5]. ADC12 Al-Si alloy has the composition of Si at 11.3 wt.% according to Farahany et al. [6]. At the same time, study from Indarsari et al. [5] stated that the composition of this alloy is about 9.5-12.6 wt.%.

Since the composition of Si is between the hypoeutectic phases of Al-Si (5 to 12.6 wt.%), the alloy elements contained inside this alloy are α-Al and Al-Si eutectic [1]. Song X. et al. studied that plate-like microstructure shapes are because of a soft Al matrix containing silicon particles [4]. There are many ways to change the plate-like shapes of eutectic Si grains such as superheating, chemical modification and vibration [7]. The addition of rare earth materials could refine eutectic Si grains from the plate-like structure into the fibrous structure [8]. Dias et al. [9] studied the effect of Bi addition on Al-Si alloy. They found it helps to change large plate-like Si into the lamellar structure by refining the shape. Moreover, adding Sr into the alloy also causes in dendritic changes into the equiaxed structure for eutectic Si grains, but too much Sr can lead to the formation of intermetallic compounds that reduce the mechanical properties [5]. Song X. et al. found that the addition of Pr can lead to the refinement of the primary morphology of the alloy, resulting in a decrease in wear rate and increased hardness and tensile properties of Al-Si alloy [4].

This study used Pr to refine the ADC12 Al-Si alloy microstructure and enhance the mechanical properties. The effect of Pr addition with different concentration (0.1, 0.3, 0.5, and 1.0 wt.%) on ADC12 Al-Si morphology was observed using OM and SEM. In addition, tensile tests were performed with a 1 mm/min cross-head speed to determine the alloy's strength.

Materials and Methods

Sample Preparation

The composition of ADC12 Al-Si used to prepare casting samples is shown in Table 1. The pure industrial-grade ADC12 Al-Si (99.9 %) and Pr (99.9 %) were used to fabricate the ADC12 Al-Si with Pr. ADC12 Al-Si ingot was melted by placing it in a 10 kg graphite crucible, and the material was heated using an electrical resistance furnace at 740 ˚C for 20-30 minutes. After ADC12 Al-Si was melted, 0.1 wt.% of Pr was added. Following that, the molten alloy was poured into a cast-iron mould that has been preheated to 250 ˚C. Next, the molten metal was manually stirred using a stainless-steel rod, which occurred for about 5 minutes. The procedure was repeated for 0.3, 0.5, and 1.0 wt.% of Pr to produce various Pr concentration in the ADC12 Al-Si.

Table 1: The chemical composition of ADC12 Al-Si alloy

Element	Al	Si	Fe	Cu	Ti	Mg	Zn	Ni	Cr
Wt.%	Bal.	10.5	0.864	2.33	0.0462	0.221	0.817	0.0759	0.0389

Characterizations

Before undergoing characterisation, the casting samples were cut into small pieces to make the observation process easier. First, the samples were ground using 250, 500, 1000, 1500, 2500, and 4000 grits of abrasive paper until the surface is smooth. Next, samples were polished using a polishing disc covered with soft velvet cloth and colloidal silica (0.5 µm) agent to produce a mirror-like surface. Finally, the samples were etched using 0.5 % of HF acid for 10s. The samples were observed using an optical microscope (OM) for microstructural analysis. The backscattered images were captured by a scanning electron microscope (SEM) at 500x to 1000x magnification. The presence of elements in the alloy was determined using the EDS.

Tensile Test

The sample was attached to the tensile testing machine (Instron-5982) by clamping it at both ends with a constant cross-head speed of 1 mm/min for conducting the tensile test. The tensile strength of all samples was plotted using the data produced from this test. The sample size for this test is 25 mm, 6 mm, and 5 mm for length, width, and thickness, respectively according to ASTM E8/E8M standard, as shown in Figure 1. The stress-strain curve was plotted using this data.

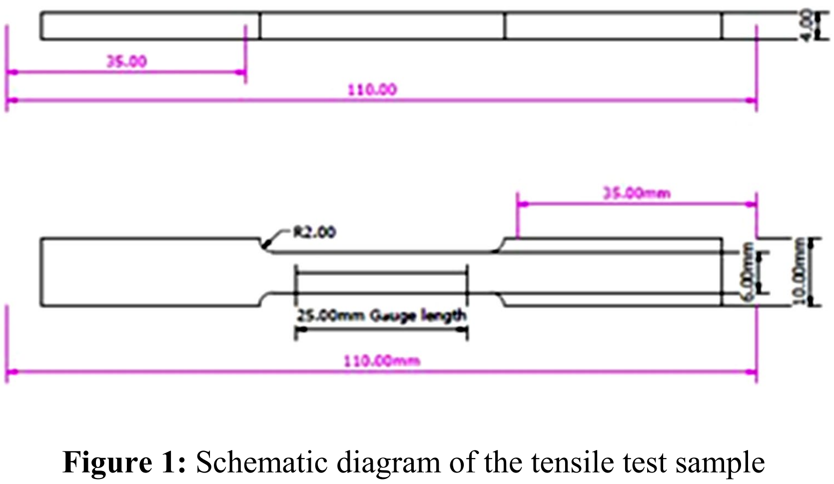

Figure 1: Schematic diagram of the tensile test sample

Results and Discussion

Optical Microstructural Analysis

The microstructure of ADC12 Al-Si alloy samples with and without Pr addition is shown in Figure 2. The microstructure of unmodified ADC12 Al-Si alloy is depicted in Figure 2(a), which contains primary phase (α-Al) and eutectic Al-Si mixture with plate-like eutectic Si particles. As the amount of Pr added as 0.1 wt. %, the size of eutectic Si became thicker and longer, as presented in Figure 2(b). This amount of Pr does not show the refinement of eutectic Si since the morphology is coarser than the unmodified sample. Figure 2(c) shows that the morphology of eutectic Si seems to be uniform, but there are many grains produced and still coarse when the addition of Pr is 0.3 wt.%. Eutectic Si grains size was refined from plate-like to lamellar shape as the percentage of Pr is 0.5 wt.% and there are many spaces between eutectic Si grains to each other, as can see in Figure 2(d). The length and thickness of eutectic Si grains were lowered, resulting in a reduction in the size of intermetallic compounds. According to Figure 2(e), the addition of 1.0 wt.% Pr to the ADC12 Al-Si alloy will increases the size of eutectic Si grains and coarsens. This effect is caused by a phenomenon known as over-modification, in which Pr poisons the growth site of eutectic Si grains as the interfaces advance [10].

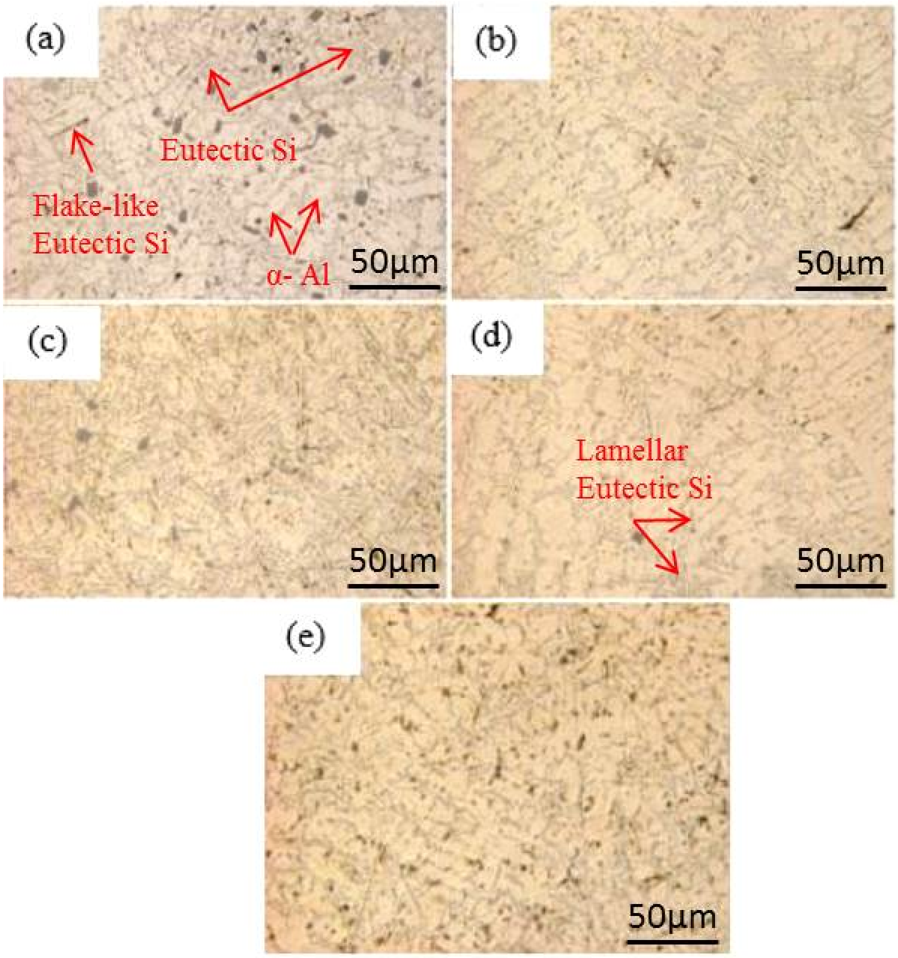

Figure 2: Optical images of ADC12 Al-Si alloy with different Pr addition for (a) base, (b) 0.1, (c) 0.3, (d) 0.5 and (e) 1.0 wt.%

Scanning Electron Microscope Analysis

The SEM micrographs of ADC12 Al-Si alloy added with different content of Pr (0.1-1.0 wt.%) is shown in Figure 3(a) to (d). It can be observed that with addition of 0.5 wt.% Pr the most modification of eutectic Si grains achieved, in which their morphology becoming shorter and thinner. The morphology of eutectic Si grains is similar to that of small, fiber grains. When Pr is added at a content of 1.0 wt.%, eutectic Si grains grow again. The length and thickness of grains increase because of over-modification phenomenon. As a result, ADC12 Al-Si alloy owns a coarser microstructure.

Figure 4 and 5 shows the EDS analysis of 0.5 and 1.0 wt.% of Pr respectively, it determines the exact composition of elements inside the samples. The EDS pattern shows a presence of Pr on the eutectic Si grains that refine the grains by producing intermetallic bonding in the alloy matrix [4]. The dislocation between α-Al and intermetallic compounds is reduced when refined eutectic Si grains [11]. However, according to Hume-Rothery rules, if the alloy contains too much Pr, it will undergo inversion modification [10]. As a result, Pr is unable to enter the α-Al phase and begin to gather around the eutectic Si grains, giving the appearance of thicker and longer eutectic Si grains in SEM analysis.

The composition of Al, Si and Pr in ADC12 Al-Si alloy with differing amounts of Pr is shown in Table 2. The mass percentage for Si decreases when 0.5 wt.% Pr is added to the alloy but increases when 1.0 wt.% Pr is added. It established that 0.5 wt.% of Pr is optimal content for refining eutectic Si grains. On the other hand, 1.0 wt.% Pr will increases the size of eutectic Si grains, resulting in an over-modification phenomenon.

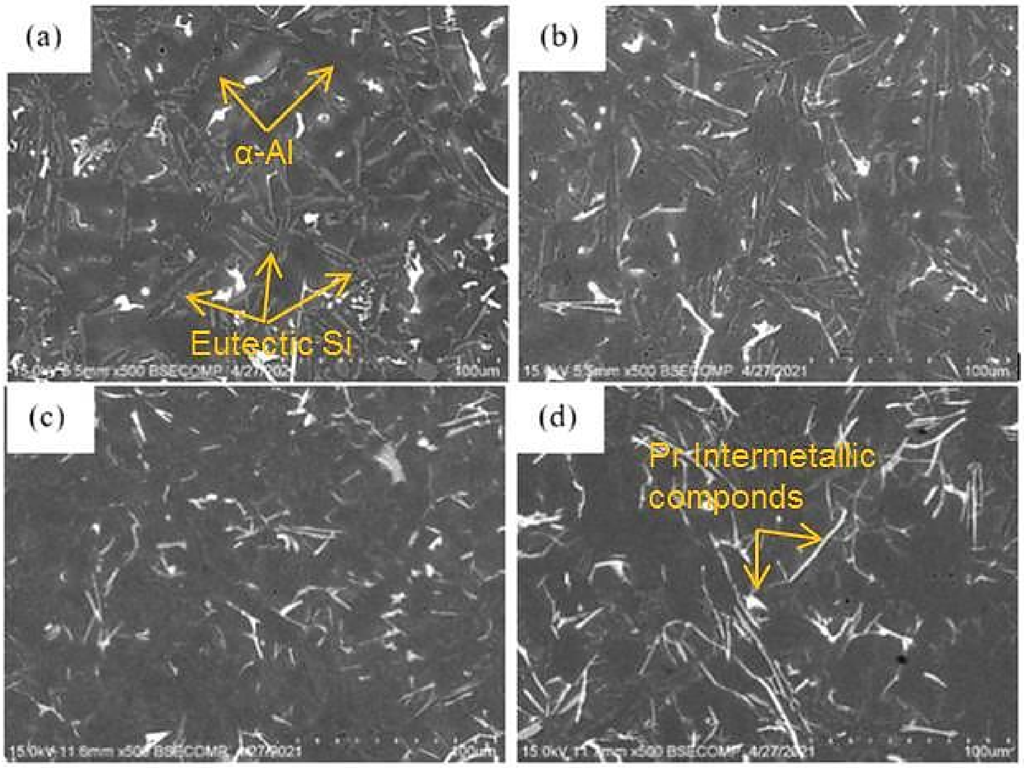

Figure 3: SEM images of ADC12 Al-Si alloy with addition of Pr for (a) base, (b) 0.1, (c) 0.5 and (d) 1.0 wt.%

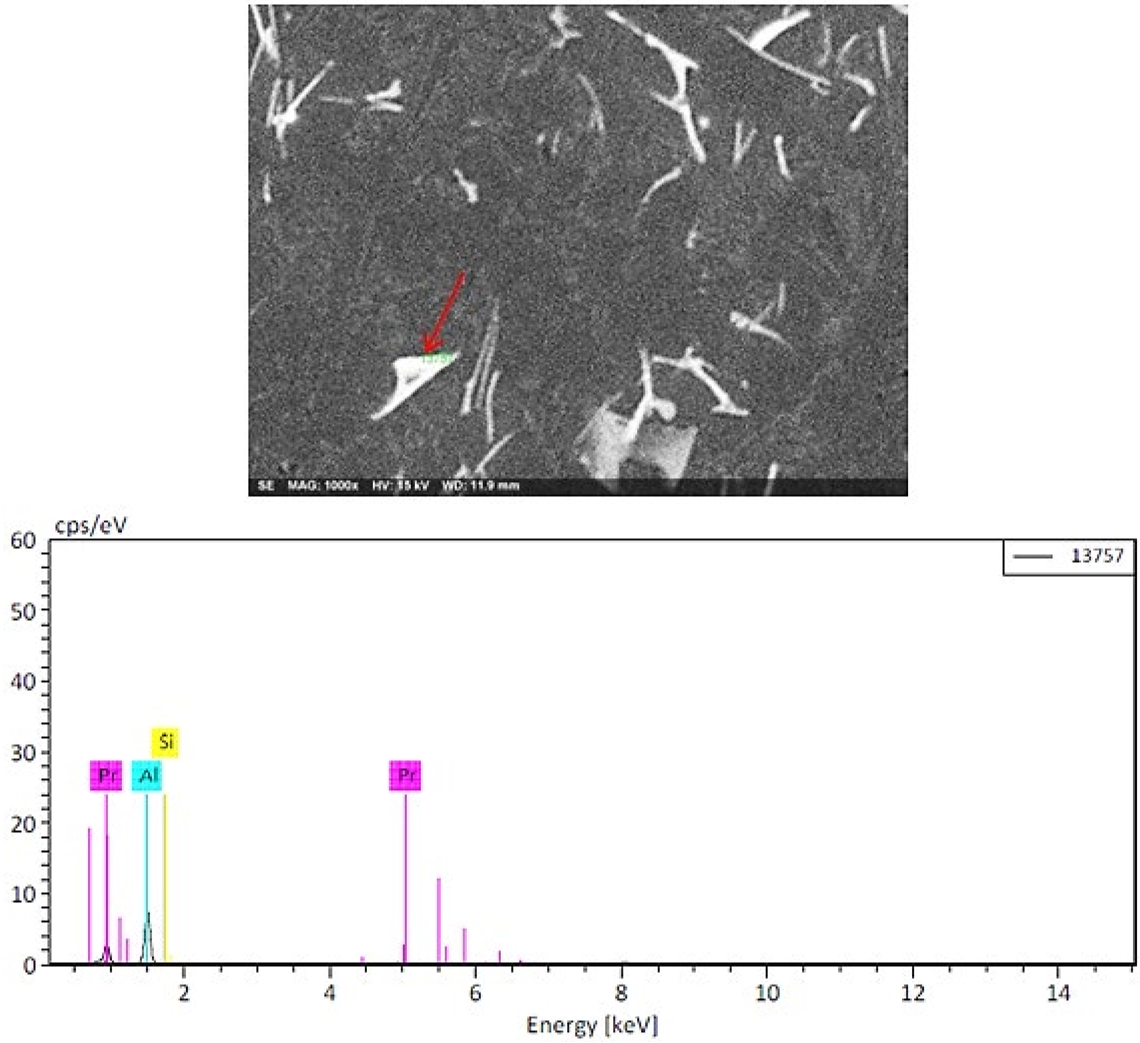

Figure 4: EDS analysis of ADC12 Al-Si alloy with 0.5 wt. % of Pr

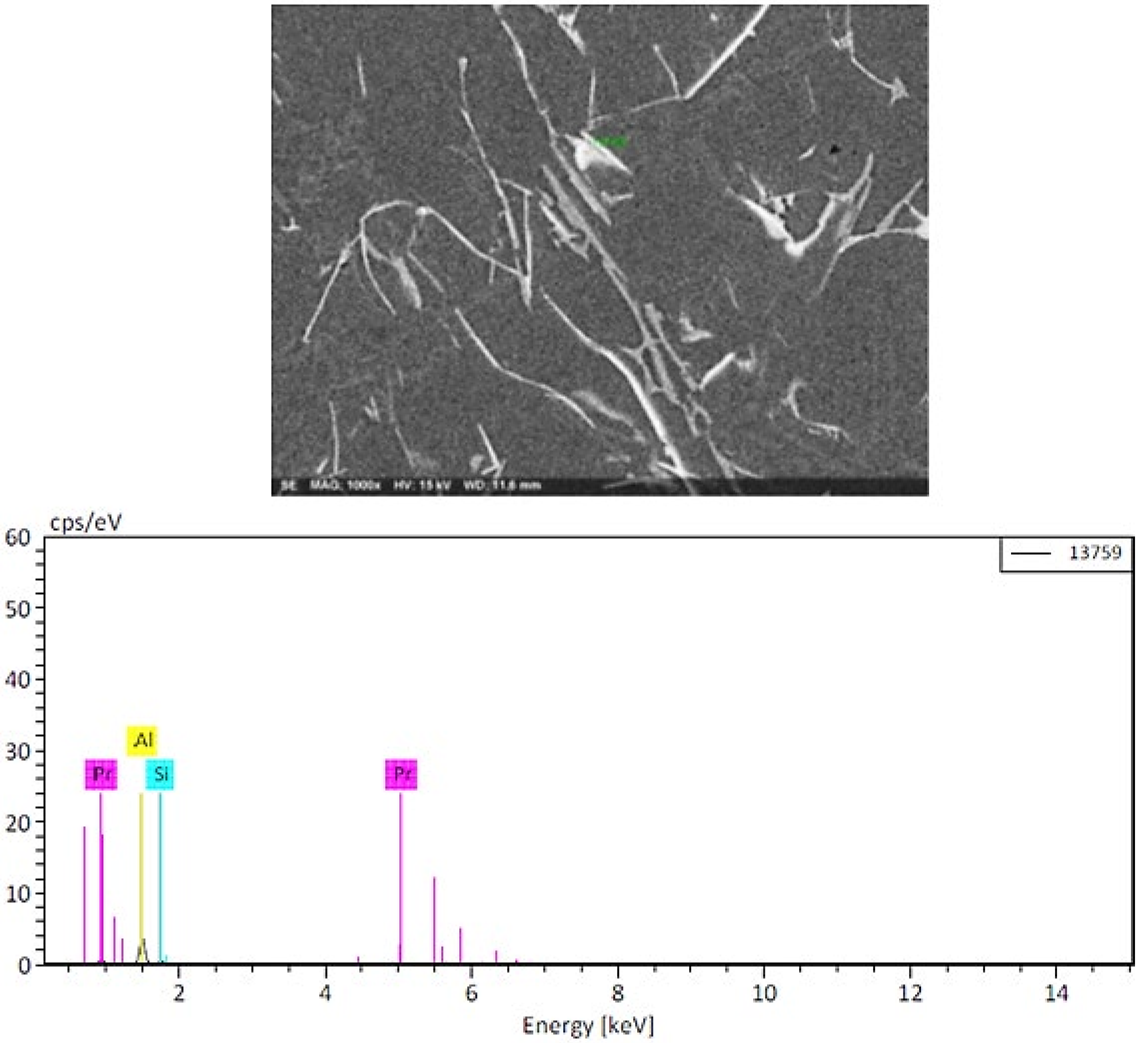

Figure 5: EDS analysis of ADC12 Al-Si alloy with 1.0 wt.% of Pr

Table 2: The composition of ADC12 Al-Si alloy obtained from EDS analysis

	Al	**Si**	**Pr**
Base	12.9	1.93	0
0.5 wt.%	20.54	0.05	5.61
1.0 wt.%	19.33	2.55	9.37

Quantitative Analysis of Si Particles

Figure 6 shows the aspect ratio of eutectic Si grains for ADC12 Al-Si alloy determined according to the equation (1). As shown, the amount of Pr is from 0.1 to 0.5 wt. %, there is a decrement of the graph trends. From here, it shows that the addition of Pr refines the eutectic Si grains. With the amount of 0.5 wt.% Pr, the aspect ratio for eutectic Si decreased to 6.15 (42.31 %) from the unmodified sample. But, the addition of 1.0 wt.% Pr shows the aspect ratio increment for eutectic Si grains where it increased to 9.58 (35.80 %)

from a sample containing 0.5 wt.% Pr. Even though the aspect ratio value at 1.0 wt.% is less than the unmodified sample, it is still not the optimum value to modify this alloy. The increased aspect ratio is due to the high content of Pr gathered around the eutectic Si grain boundary instead of entering the crystal lattice of the primary phase of α-Al.

$$\text{Mean aspect ratio} = \frac{1}{m}\sum_{j=1}^{m}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{a_i}{b_i}\right)_i \tag{1}$$

Where ai, and bi are the longest and shortest dimensions of a single eutectic Si particle respectively, n is the number of Si particles measured in a single field (0.60126 mm^2), and m is the number of the evaluated fields.

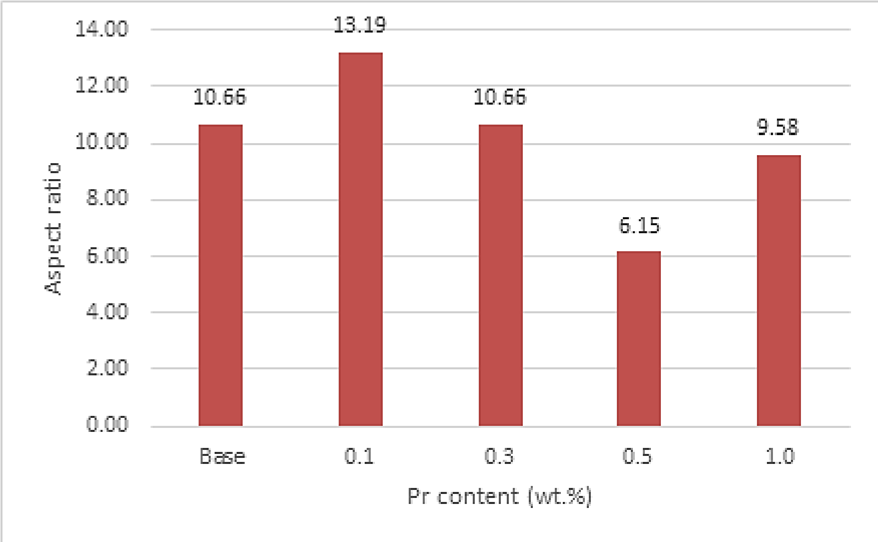

Figure 6: Aspect ratio values of Pr added ADC12 Al-Si alloys

Tensile Properties

Figure 7 shows the tensile results of ADC12 Al-Si alloy with the addition of Pr (0.1, 0.3, 0.5 and 1.0 wt.%). Roughly, by looking at the curve trends, ADC12 Al-Si alloy is a brittle material due to coarse eutectic Si grains, but when it was added with Pr, its brittleness decreased due large plastic deformation region that indicates it has a large amount of fracture. With the addition of 0.5 wt.% Pr, it has a larger area under the stress-strain curve when compared with the unmodified sample. The area under the curve demonstrates the toughness of the sample. Due to this, 0.5 wt. % Pr able to absorb a large amount of energy before it failed. The addition of 1.0 wt.% resulted in a significant area under the curve when compared to the unmodified sample. However, when 0.5 wt. % Pr is used, the area under the curve is reduced. Additionally, a 1.0 wt. % Pr elongation path was shown to be less than 0.5 wt.% Pr.

Figure 8 proves that UTS and elongation value of 0.5 wt.% Pr has the highest value among the other amount of Pr added to the ADC12 Al-Si alloy. This amount of Pr can withstand the stress applied up to 111.86 MPa with a strain value of 0.016 compared with unmodified sample stress at 93.18 MPa with a strain of 0.0114. The performance of alloy is increased to 20.05 % and 40.35 % for both stress and strain. But, the performance of this alloy decreased as Pr content in the alloy was 1.0 wt.% as this sample failed at the stress of 110.15 MPa and strain of 0.0129. Addition of 1.0 wt. % Pr reduces the performance of the optimum amount of Pr to 18.21 % and 13.16 % for stress and strain, respectively.

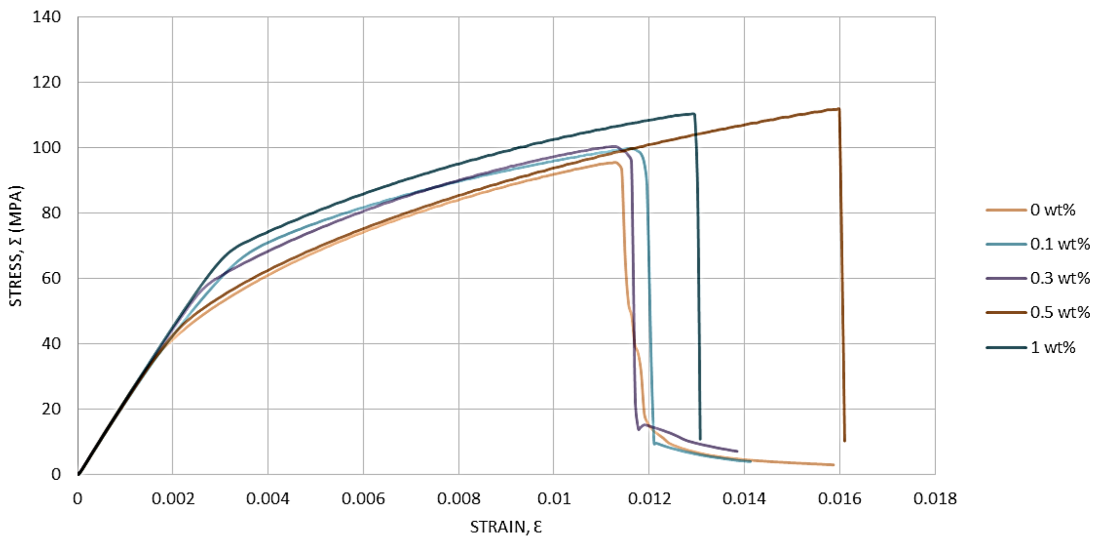

Figure 7: tress-strain curve of ADC12 Al-Si alloys with different content of Pr (0, 0.1, 0.3, 0.5, and 1.0 wt.%)

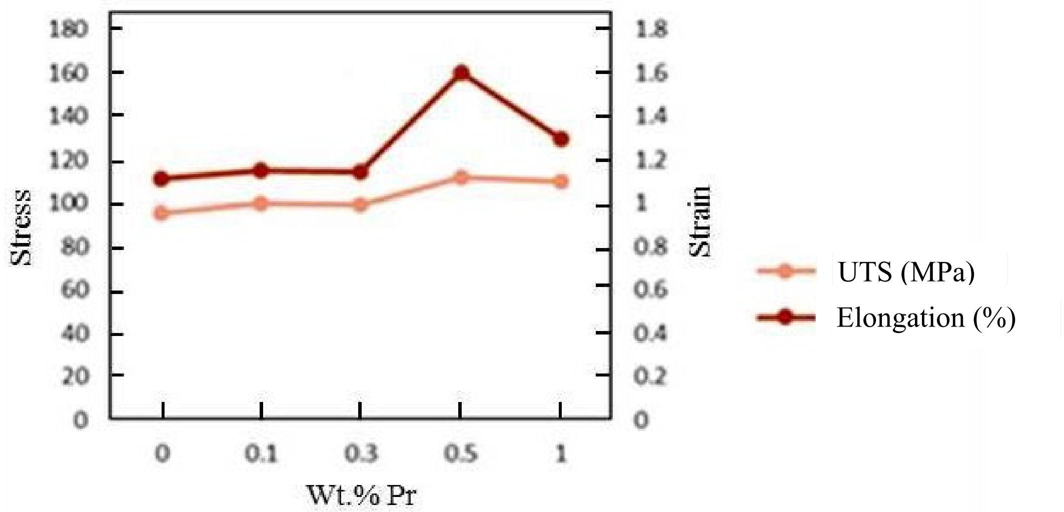

Figure 8: Tensile properties of ADC12 Al-Si with different content of Pr; ultimate tensile strength (UTS), yield strength (YS) and elongation

Conclusions

In conclusion, the size of eutectic Si grains changed as the content of Pr in the ADC12 Al-Si increased by 0.1, 0.3, 0.5, and 1.0 wt.%. The morphology of the eutectic Si grains changed from plate-like to lamellar-like structures. Eutectic Si grains length and thickness started to decrease when the Pr content was at 0.1 to 0.5 wt. %. But, it began to increase again when the Pr content was at 1.0 wt.%. Therefore, the optimum amount of Pr content added to the ADC12 Al-Si alloy is 0.5 wt.%, and it can be justified when calculating the aspect ratio value. The alloy undergoes a poisonous effect when adding of Pr content is at 1.0 wt.% due to the increasing size of eutectic Si grains in aspect ratio. The ultimate tensile strength of alloy has a higher value than the other samples when it reaches the optimum percentage of Pr (0.5 wt.%). Elongation of 0.5 wt.% Pr also owns the higher value by comparing the improvement of strength between unmodified sample and sample with 0.5 wt.% Pr, the ultimate tensile strength and elongation had improved by 20.05 % and 40.35 %, respectively. However, the performance of ADC12 Al-Si alloy decreased as Pr was at 1.0 wt.%. The ultimate tensile strength and elongation were reduced by 1.81 % and 27.19 %, respectively, compared to the sample 0.5 wt.% Pr. The excessive amount of Pr reduced the mechanical properties of ADC12 Al-Si due to the increment of eutectic Si grain size.

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Author Contributions

All authors contributed to data analysis, drafting and critically revising the paper, and agreeing to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare

Compliance with Ethical Standards

The work is compliant with ethical standards

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