Penerbit Akademia Baru

Malaysian Journal on Composites Science and Manufacturing

Journal homepage:
https://www.akademiabaru.com/submit/index.php/mjcsm/
ISSN: 2716-6945

Impact, Hardness and Fracture Morphology of Aluminium Alloy (Al-Si) filled Cobalt Oxide Nanoparticles at Various Stir Casting Temperatures

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ARTICLE INFO

Article history:
Received 27 June 2021
Received in revised form 12 July 2021
Accepted 12 July 2021
Available online 30 July 2021

Keywords:

Stir-Casting, Al-Si, CoO nanoparticles, impact toughness, hardness, fracture morphology

ABSTRACT

The automotive and aviation fields require engineering materials that can save and optimise fuel consumption. Unique characteristics of lightweight, higher strength to weight ratio, good corrosion resistance, and good castability are indispensable for castable metal such as Silicon Aluminium (Al-Si). The mechanical properties of Al-Si could be further improved through the addition of Cobalt Oxide (CoO) nanoparticles during the casting process. The importance and purpose of this study were to determine the impact toughness, hardness and fracture morphology of Al-Si metal alloy filled with 0.015 wt.% CoO nanofiller at the various melting temperature of 750 °C, 800 °C and 850 °C. The stir casting method was utilised considering the most appropriate method for mixing nanoparticles powder into the Al-Si matrix. Three test specimens were prepared for each temperature variation. Impact testing using the Charpy method (ASTM E23-56 T) and hardness testing using Rockwell Superficial HR15T and fracture morphology obtained from impact testing fractures were performed accordingly. The impact test results showed that the Al-Si added with 0.015% CoO at 800 °C of melting temperature possessed the highest impact toughness value of 25.111 x 10^{-3} Joule mm^{-2} than the other variations. The hardness test results showed that Al-Si added 0.015% CoO with a melting temperature of 850 °C had the highest hardness value of 79.52 HR15T. The fracture morphology of the impact test in all specimens shows uniform brittle fracture characteristics. It is found that the melting temperature during the stir-casting process of Al-Si has played a significant role in influencing the resulted properties of Al-Si filled CoO nanoparticles metal matrix composites. The selection of an accurate melting temperature for the stir casting process will affect the resulted properties of produced metal composites.

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https://doi.org/10.37934/mjcsm.5.1.1120

1. Introduction

The growing market demand in the automotive and aerospace industries to reduce energy consumption and produce more fuel-efficient vehicles continues to be a major challenge. Aluminium-silicone alloy (Al-Si) had increased market demand for an automotive industry that replaced ferrous materials. Al-Si alloys are widely used in the automotive industry as a sustainable replacement to cast iron in the manufacturing of machine components because of their high strength-to-weight ratio, high toughness, good corrosion resistance, and good castability [1-2]. Apart from the high strength-to-weight ratio characteristic, Al-Si alloys also have the main advantage of excellent thermal conductivity, which allows the combusted heat to be dissipated more quickly than cast iron [3]. However, to enhance the performance of Al-Si alloys that meets the requirements of final applications, several modifications need to be made, such as through the addition of inorganic filler. The addition of filler could enhance the mechanical and thermal performance of Al/Si-based composites.

Previous research has investigated that the Al-Si alloys reinforced with TiC and $ZrSiO_4$ filler that are fused using a stir casting method show increased mechanical properties at the addition of 15 wt.% filler loadings [4]. One reinforcement type that can be used for aluminium alloys is cobalt oxides (CoO) nanoparticles. Increasing loading of CoO nanoparticles has increased the yield stress, ultimate tensile stress, and modulus of elasticity of produced metal composites [5]. But the relationship between the filler added to the melting temperature of Al/Si alloys during the stir casting process is still not being understood. Hence, it is hypothesised here that the higher the temperature, the better the resulted properties of produced Al/Si-CoO composites.

Cobalt oxide is one of the most abundant inorganic minerals on earth, which has good environmental compatibility and has become the focus of attention in various research fields. There are four types of cobalt oxide, namely cobalt (II) oxide (CoO), cobalt (III) oxide (Co_2O_3), cobalt(IV) oxide (CoO_2), and cobalt(II.III) oxide (Co_3O_4). The Co_3O_4 and CoO are the most commonly used types due to their excellent thermal stability and outstanding physical and chemical properties [6]. The Co_3O_4 is an important oxide material widely used in catalysis, gas sensors, electrochromic films, battery cathodes, heterogeneous catalytic materials and magnetic materials [7].

The stir casting process using the mechanically based stirring technique is widely used to produce aluminium based matrix composites reinforced by ceramic micro and nanoparticles [8]. This casting method is considered a cheaper and very economical process. Another advantage is that the stir casting method is simple, flexible, and can produce alloys with large volumes and produce large-sized components [9].

Stir casting is the liquid-phase composite fabrication in which ceramic particles (non-metallic particles) are mixed with metal using the mechanical agitation approach. In the stir casting method, a vital process parameter exists: the stirring speed, which is essential for bonding between the matrix and reinforcement, that responsibly makes flowability (wettability) and a homogeneous mixture of both constituents [10]. Then, other parameters that can affect the stir casting process results are the stirring period, blade angle of the stirrer, pouring temperature, and the addition of reinforcing elements [11]. Therefore, the stir casting melting temperature effects were evaluated. Combining Al-Si alloys with the addition of CoO nanoparticles was expected to get better properties than ordinary Al-Si without the filler addition. Then the toughness, hardness and fracture morphology were evaluated in this study by focusing on the effect of various melting temperatures.

2. Methodology

2.1 Materials

The materials used in this study were 0.66 grams of Cobalt Oxide (CoO), and 5.25 kg of Aluminium Silicon (Al-Si) alloys with four melting temperature variations (three test specimens for each variation). In 3 variations of Al-Si with the addition of CoO, 0.015% of the mass of CoO was 0.22 g with raw Al-Si of 1.50 kg. The balance weight of Al-Si was used to cast Al-Si without the addition of CoO.

2.2 Methods

For stir casting procedure, about 1.50 kg of Al-Si alloy material was melted in a smelting furnace with an initial temperature of 750 °C then was added with 0.22 g of CoO filler with stirring for about 90 seconds, after which the temperature was increased again according to variations in melting temperature; 750 °C, 800 °C and 850 °C. The Al-Si metal without the addition of CoO as a control sample was cast in the same way at a melting temperature of 750 °C. Specimens that have been cast were then subjected to a machining process for Charpy impact testing using the ASTM Designation E23-56 T standard (Figure 1) [12]. The fracture surfaces of samples were obtained from the fracture impact test results. The hardness test used the Rockwell Superficial HR15T hardness tester, and it was carried out on the specimen after experiencing an impact testing.

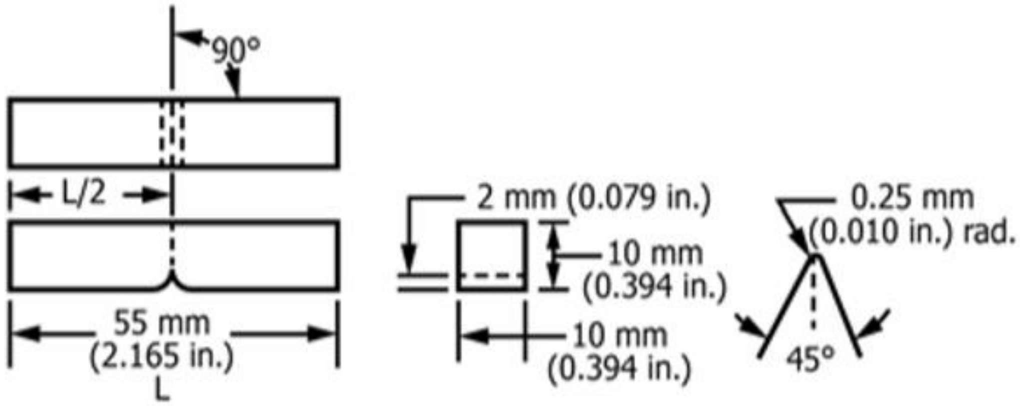

Fig. 1. Sample geometry for impact test [11]

3. Results

3.1 Analysis on impact strength results

Figure 2 displays the plots of averaged impact strength value for all Al-Si composite specimens with various melting temperatures. The highest average impact value was found in Al-Si specimens with 0.015% CoO melted at a melting temperature of 800 °C with a value of 25111 x 10^{-3} Joule/mm^2. This value is much increased compared to the Al-Si alloy without the addition of CoO filler, with about the average impact value of 17066 x 10^{-3} Joule/mm^2. An increase in impact value up to 32.04% could explain the effective contribution of melting temperature at 800 °C to increase interaction between the added CoO filler with the Al-Si metal matrix. Good interface and inter-phase interaction between both phases have ensured enough energy absorption due to delayed fracture rate during the impact loading. This temperature is considered optimum to give maximum toughness effects of produced Al-Si/CoO composites. However, at a temperature lower than 800 °C, it was found that the impact strength value had diminished to minimal due to the incomplete melting of Al-Si alloys which hindered good interaction between the metal matrix and inorganic fillers. This situation has allowed the formation of many defects and phase separation, which acted as stress concentration points prone to premature failure due to sudden impact forces. The decrease in the averaged impact strength value also occurred in the specimens of Al-Si filled 0.015 wt.% CoO at melting temperatures of 850 °C. Higher temperature may degrade the performance of CoO filler within the Al-Si matrix alloy. This may be related to the disturbance of CoO particles flow in highly viscous metal matrix at higher melting temperature due to metal vaporisation, hindering the matrix-filler interaction [13].

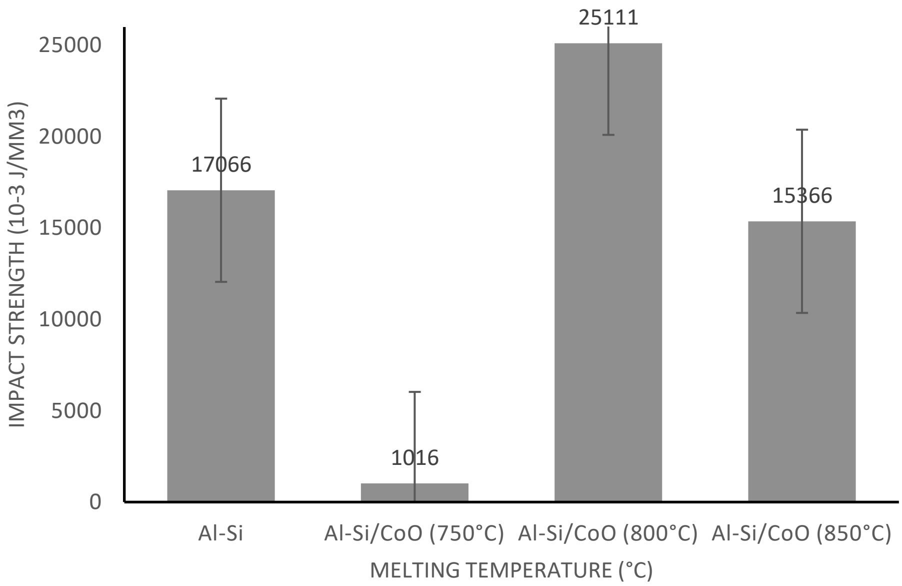

Fig. 2. Averaged impact strength value for Al-Si/CoO composites at various melting temperatures

This overall impact test finding shows that the addition of 0.015% CoO to Al-Si will not increase Al-Si metal composites' toughness if it does not melt at an appropriate melting temperature at 800 °C. The distribution of particles in the metal-alloy strengthening is essential, and the distribution of particles greatly affects the mechanical strength of the material [14]. It was found that the melting temperature influences the distribution of these particles in this study. The melting temperature here is predicted to control the distribution of CoO particles in the Al-Si matrix, as depicted in Figure 3 [13]. This difference in filler particle distribution is expected to occur in the solidification stage, where this process requires different times because it uses different melting temperatures [15]. Therefore, higher melting temperatures will require a longer solidification time. The distribution of reinforcing particles is not homogeneous due to a longer crystallisation time.

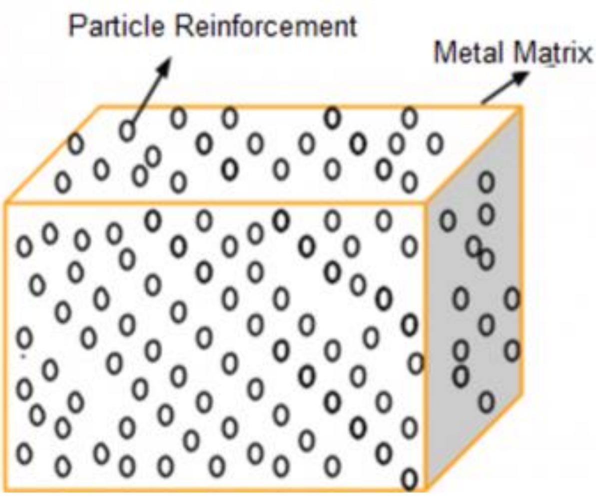

Fig. 3. Representation of reinforcing particles distribution in metal alloys matrices [13]

3.2 Analysis of hardness test results

Superior hardness characteristic is needed for materials used as components exposed with higher compressive and friction loads [16]. In this study, hardness testing was carried out using the Rockwell superficial hardness testing machine with steel ball indenter of 1/16 inch, according to the ASTM E18 testing standard. The test was carried out into 12 specimens with four sample variations and each variation having three test specimens. Increased hardness value due to the addition of 0.015% CoO filler has minimally recorded at 14.98% of positive improvement. This is shown in the following Figure 4. The entire composite samples with the addition of 0.015% CoO filler has experienced an increase in their hardness value. The highest value of hardness is recorded for Al-Si/0.015 wt.% CoO composite at a melting temperature of 850 °C, with a hardness value of 79.52 HR15T. While for Al-Si alloy (control sample), the hardness value is only 67.61 HR15T.

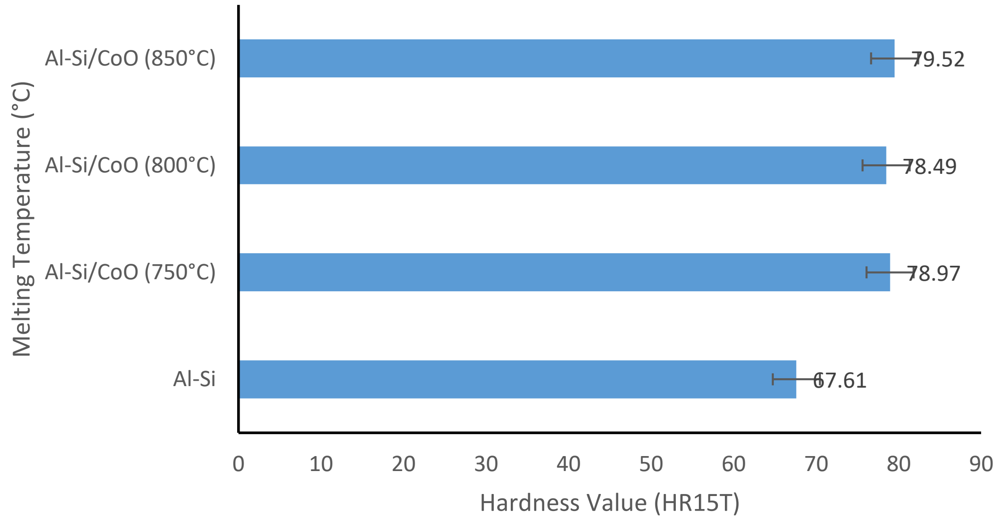

Fig. 4. Averaged hardness value (HR15T) for Al-Si/CoO composites at various melting temperatures

This phenomenon can be explained due to the CoO filler particles' efficacy, which makes the Al-Si metal alloy granules denser because they are tucked into CoO particles, thereby increasing the mechanical strength of produced composites, especially in this test. The formation of granules clustering had increased the material's resistance toward local deformation. According to Kannan (2017), the addition of metal reinforcement to the precipitation strengthening mechanism was related to the Hall-Petch equation. Based on the Hall-Petch theory, the smaller the grain size, the better the mechanical properties of produced material, especially the value of hardness. The Hall-Petch equation can be seen in the following Equation 1 [17]:

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \quad (1)$$

where, σ_y is the yield point, σ_0 is a certain shear stress, k_y is a constant individual for each material, known as the Hall-Petch parameter. From the equation, the value of d refers to the grain size, which is inversely proportional to the material's mechanical properties. The analysis is supported by the results of microstructure observation, evaluated by Saputra [18] using a similar material system, which found that the addition of 0.015% CoO has changed the formation of the grains. The grains in the Al-Si specimen without CoO addition have appeared larger and more even size, but with the addition of 0.015% CoO, more grains are formed, uneven in size and varied in its form and shape. By interrelating into this study, it can be said that the melting temperature factor had significantly contributed further to alter the grain growth in Al-Si/CoO metal composite system, which at the end increased the resulted mechanical performances.

3.3 Fracture surface observation

Figure 5 depicts the fracture surface morphologies of the impact test specimens, which represents each sample variation. It can be seen from all the fracture surfaces that the fracture types are obviously brittle type fractures. Ductile fracture types cannot be observed in all specimens, but porosities are still observed at all fracture surfaces. It is reported that porosities due to macrosegregation are common in the Al-Si processing using the conventional casting method [19]. The porosities in fractographs were indicated by the highlighted red circles. It can be clearly seen that the Al-Si specimen at a melting temperature of 750 °C for both specimens with and without CoO filler reinforcement has more porosity than other fabricated specimens at different melting temperatures. This shows that the specimen with a melting temperature of higher than 750 °C has relatively smooth fracture surfaces. The observed porosity is not as large as the porosity presence at samples produced at 750 °C Tm (melting temperature). This phenomenon similarly occurs in the previous research conducted by Gong et al. [20]. Al-Si cast at a higher melting temperature showed less porosity, and the fracture surfaces are smoother. Based on these observations, the higher melting temperature could affect the porosity formation of Al-Si because it is suspected that the higher melting temperature causes the release of trapped air due to the stirring process in the alloy matrix. This analysis is supported by the previous research [15]. This observation has supported the impact strength and hardness findings as discussed in the previous section.

3.4 Effects of stir casting melting temperature on the mechanical properties of Al-Si/CoO composites

Figure 6 displays the plots of effects on various stir casting melting temperatures to the mechanical properties of Al-Si metal alloy with the addition of 0.015% CoO filler. It can be clearly seen in Figure 6 the plotted trend that is mutual inversely proportional between the impact strength value and the resulted HR15T hardness of produced metal composites. The fracture surface observation for Al-Si with the addition of 0.015% CoO filler melted at the temperature of 750 °C found the presence of porosity, which responsibly induced lower impact toughness value compared to filled Al-Si composites. The impact toughness is highest in Al-Si variation with added 0.015% CoO filler, melted at 800 °C temperature. This has been supported with the fracture surface showing a less brittle configuration than other sample variations. The highest hardness value belongs to Al-Si with 0.015% CoO filler, melted at 850 °C temperature, indicating the most brittle fracture and characteristic of fracture surfaces, which is directly proportional to the hardness test results, as shown in Figure 6.

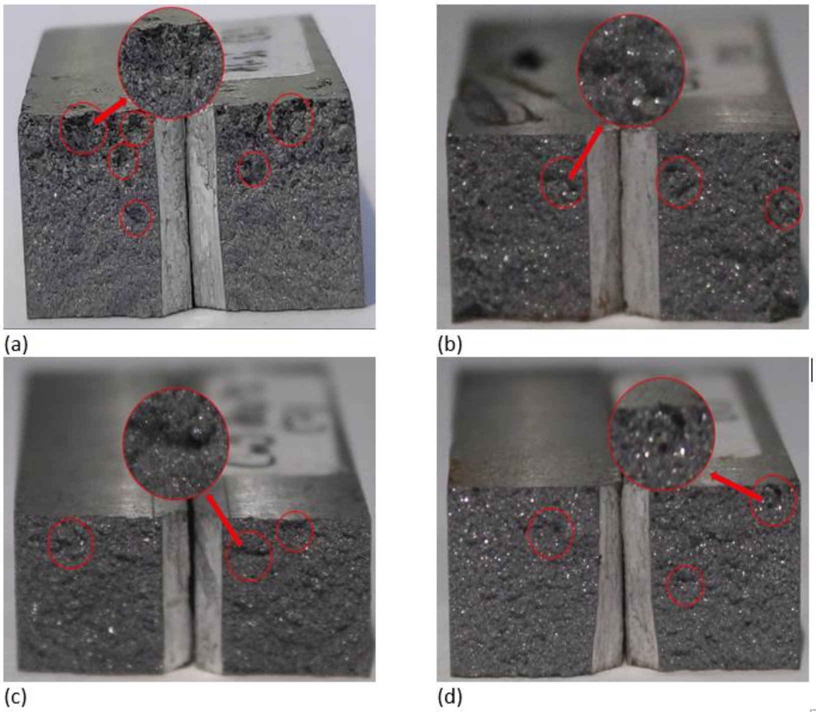

Fig. 5. Fracture surface morphologies of: a) Al-Si; b) Al-Si/0.015% CoO at 750°C T_m; c) Al-Si/0.015% CoO at 800°C T_m; d) Al-Si/0.015% CoO at 850°C T_m

The findings on impact and hardness correspond to the previous works reported by Datau [21] and Libu [22]. The impact strength results representing toughness are inversely proportional to the hardness results, demonstrating materials resistance towards local deformation for produced Al-Si based metal alloy filled composites. This phenomenon would be interesting to be explored further.

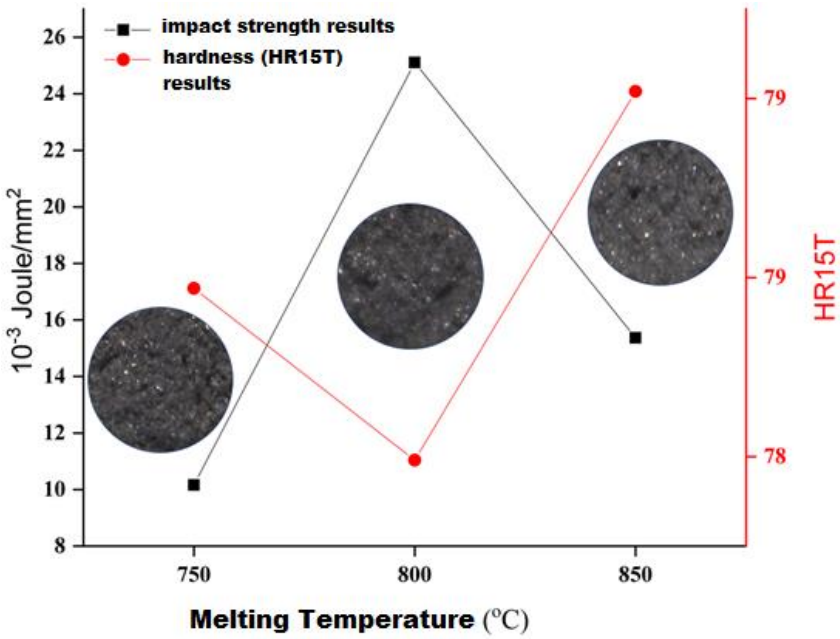

Fig. 6. Effects of stir casting melting temperature on the mechanical properties of Al-Si/CoO composites

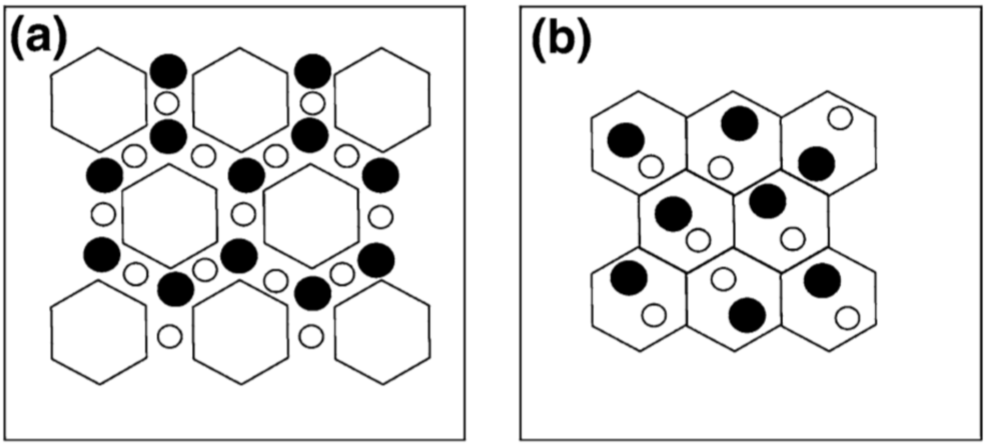

Fig. 7. The possible distribution of reinforcement in items a) bounded by items; b) within items [15]

Figure 7 shows the possible distribution of reinforcing filler in the metal matrix. It can be seen in Figure 7 that the reinforcing filler particles are distributed at grain boundaries of the metal matrix (a) and distributed within the matrix grains (b). This phenomenon is thought to occur where the CoO reinforcing filler particles is distributed into or to the grain boundaries of the Al-Si metal alloy matrix. The value of the mechanical strength varied when the grain had experienced changes in its size and shape due to fillers and manipulation of melting temperature in the stir casting process. Based on the results of microstructure observation as evaluated by Saputra [18] by using similar matrix material, the addition of 0.015% CoO had caused a noticeable change to the grain size. The granules in the Al-Si specimen without CoO appear to have a larger and more even size configuration. Still, with the addition of 0.015% CoO inorganic filler particles, it seems that more and more grains are formed, uneven in size and varied in shape. Hence, from this study, it was found that the addition of

CoO filler and melting temperature of the stir casting process are significantly relevant and influencing the resulted properties of Al-Si based metal matrix composites.

4. Conclusions

Overall, this study is vital to evaluate the effects of stir casting melting temperature towards the hardness and impact strength performance of Al-Si alloys filled CoO filler. Al-Si metal alloys with the addition of 0.015 wt.% CoO filler particles have been successfully prepared using the stir casting method at various melting temperatures of 750 °C, 800 °C and 850 °C. The impact strength results show that Al-Si filled 0.015 wt.% CoO melted at 800 °C possessed the highest impact strength value or toughness of 25.111 x 10-3 Joule/mm^2 compared to other variations. The percentage increase in impact strength value is 32.04% as compared to the unfilled sample. The hardness results (HR15T) shows that the Al-Si filled 0.015 wt.% CoO filler particles melted at 850 °C had the highest hardness value of 79.52 HR15T. The percentage increase in the hardness value is about 14.98% in comparison to the unfilled sample. The inter-relationship between the impact strength and hardness findings are inversely proportional. The fracture morphology from the impact test results for the entire produced samples disclosed the characteristic of brittle fracture type. Hence, the addition of 0.015 wt.% CoO inorganic filler particles into Al-Si metal alloy matrix and the stir casting melt temperature selection had revealed its importance in influencing the growth and transformation of grain changes in the produced metal matrix composites samples. This study can be further extended to evaluate the other stir casting processing parameters' effects on the Al-Si filled CoO metal composites performances.

Acknowledgement
This study was fully funded by research support from Universitas Negeri Malang, Indonesia. Also, this research is one of the output from active collaboration between the Universitas Negeri Malang, Indonesia and Universiti Teknikal Malaysia Melaka (UTeM).

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