Mechanical Properties and Morphological Analysis of Copper Filled Aluminum Alloy Hybrid Matrix Composite

Muhammad Sayuti[1], Mohammad Alhajji[2] & Shamsuddin Sulaiman[2,*]

[1]Department of Industrial Engineering, Faculty of Engineering, Universitas Malikussaleh, Jalan Batam, No. 5, Kampus Bukit Indah, Blang Pulo, Lhokseumawe, Aceh 24351, Indonesia.
[2]Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
*Email: suddin1331@gmail.com

Highlights:

- New metal matrix composite material.
- Improvement of mechanical and corrosion properties.
- Vibration casting.

Abstract. This paper presents the characterization of LM6 aluminum alloy with varying copper addition. LM6 is a soft, light-weight and corrosion resistant metal. Due to these characteristics, the material was selected to be added with copper to identify improved properties. The amount of copper addition was varied from 0%wt with intervals of 3%wt for every alloying run. Vibration casting, or vibration molding, was conducted. The vibration process is said to give a better result in terms of the alloy's grain size and arrangement. Mechanical testing and microstructure analysis were performed to prove the theory. Specimens with various amounts of copper were successfully produced and tested. The LM6 alloy specimen casted without copper and with vibration casting at 20 Hz had the highest tensile strength and percentage of elongation, while the LM6 alloy specimen casted with 9%wt of copper without mechanical vibration casting had the best mechanical properties based on the overall results and criteria. The percentage of copper addition that produced the optimum properties was found to be 9%wt of copper without vibration molding (hardness 46.2HRB, 125 MPa).

Keywords: *aluminum composite; Al-Si-Cu; LM6; hybrid composite; vibration casting.*

1 Introduction

Alloys are materials that are a mixture of more than one element but contain one major element. Aluminum is widely used in alloying because of its light weight, high corrosion resistance and excellent mechanical properties compared to other metals, either in the form of a composite or a metal that contains only one element. Aluminum can be alloyed with silicon, magnesium, copper, zinc, manganese, and other elements. Each element is added based on criteria required

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for a specific usage. The combination of aluminum with silicon (Al-Si or LM6) delivers the most perfect alloy because of its casting-ability [1].

The aim of this investigation was to study the process of alloying aluminum with copper by casting. Casting is the process of making a mixture of materials, including alloys. The material is heated until the temperature hits the melting point and is then poured into a mold to produce the desired shape. The combination of aluminum and copper in an alloy is often preferred for aesthetic reasons and to withstand corrosive environments such anywhere under water, rivers, the sea, beaches, or even offshore in the oil and gas industry [2]. This is because the improved characteristics of the alloy by the addition of copper makes it highly resistant toward corrosion.

The Al-Si-Cu alloy can be varied by adding different amounts of copper (%wt). A maximum copper amount of 9%wt has been identified due to its solubility towards molten aluminum [1]. A number of questions arise: What amount or percentage of copper in the aluminum alloy produces the best properties. What type of alloy composite has the best mechanical properties and characterization? How does the molding process affect the result? There are two variations of molding, i.e. ordinary molding and vibration molding. In the process of vibration molding, different vibration frequencies can be applied [3].

Different variables, from the percentage of the copper to the frequency of the vibrating molder, can be applied to make a comparison of the produced alloy in terms of microstructure and macrostructure, grain size and other mechanical properties. To solve the research problem, this study used two variables, the percentage (%w) of Cu and type of casting, to improve the mechanical properties of the alloy to match different application requirements. The first method was by varying the percentage of copper added to LM6. Addition of copper while alloying LM6 is expected to improve its aesthetic appeal and its corrosion resistance. The second method used was mechanical vibration molding to refine the grain structure and improve the mechanical properties compared with an alloy produced without mechanical vibration molding [4,5].

This study focused on the fabrication of several different Al-Si-Cu alloy composites by using metal casting. The mold shape was kept constant by following the specifications of the ASTM B557 standard already available at the laboratory to make sure the testing results would not be affected by the design. A metallurgy study was conducted to see the macrostructure and microstructure of the Al-Si-Cu metal alloy composites in terms of grain size and arrangement, and how they affect the mechanical properties of the Al-Si-Cu alloy.

2 Materials and Methodology

2.1 Materials

Aluminum LM6 ingots, copper powder (99.99%) and molds were prepared and all alloys were molded with the same mold shape to ensure that the results from the mechanical test were not affected by it. The LM6 aluminum needed for one mold is usually 1.7 kg but in this experiment two different methods of molding were applied, i.e. non-vibration molding and vibration molding. Thus, the amount of LM6 that needed to be melted was 3.4 kg while the amount of copper added was varied without reducing the weight of the LM6 aluminum alloy.

The copper added to the molten aluminum was in powder form, which is the most suitable because of the amount needed for every alloying process is very small compared to the amount of aluminum [6]. Another reason for using copper in powder form was because of its large surface area, which makes the mixture and chemical bonding between the two elements faster. The copper was first heated in a small oven at 200 °C for 30 minutes to remove any possible moisture from the copper powder. Table 1 shows the calculation of the copper percentage for 3%wt, 6%wt and 9%wt addition.

Table 1 Calculation of copper amount.

Percentage of Copper (%)	Calculation (g)	Amount of Copper (kg)
3%wt	3400g-(100%-3%) = 102	0.102
6%wt	3400g-(100%-6%) = 204	0.204
9%wt	3400g-(100%-6%) = 306	0.306

2.2 Sample Fabrication

The alloy specimens were fabricated in a laboratory foundry using the same casting process for all LM6 alloys with different copper contents. The fabrication of the aluminum alloys started with heating of the aluminum in a furnace to its melting point of 660.3 °C. Before the temperature of the aluminum hit the melting point, a specific amount of copper was added to the foundry. The molten mass of LM6 and copper (2 min) was stirred using a mechanical stirrer to mix the elements homogeneously, with both elements having even contact for better chemical bonding, which helps to improve the alloy's properties.

After all the elements had reached their melting point, the different molten aluminum specimens with a specific copper content were divided into two different molds, i.e. an ordinary, or static, mold and a vibration mold. The molten mass was cooled down for at least 2 hours until it was completely solidified.

2.3 Testing

The aluminum copper alloy specimens then underwent mechanical testing to identify their mechanical properties. Casting the alloys with specific dimensions was done by following the ASTM B557 standard [7], where samples must have an exact width, length and height to make sure that the results of the test are valid. When the tensile test was started, a tensile load of 100 kN was automatically applied to the specimen while the software plotted the stress-strain curves at the same time.

A hardness test of the specimens was conducted to know the hardness of the aluminum/copper alloy. A hardness test machine was used to get the hardness value [8]. A Rockwell hardness test was conducted by using a hardened steel ball with a size of 1/16 inches with a penetration load of 100 kgf. Five different locations were tested on each sample to get the mean value of the readings.

Metallurgical testing is a method to reveal images of the macro and micro structures of a material. It is applicable to any kind of material, including composites or alloys. This test was conducted to study the grain arrangement of the elements contained in the alloy and to find the effectiveness of the chemical bonding between the elements, the distribution of the mixture, and the size of the grains in the alloy. Finally, this study analyzed the relationship between all of the aspects listed based on the results of the mechanical testing to see how the grain size and arrangement affect the mechanical properties and solidification time of the alloys [9].

Elemental analysis by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) spectrometry was performed on all specimens except the specimen that was casted without copper. The specimens were placed one by one and examined using a 20-kV electron beam under vacuum condition to make sure the results were not affected by any possible condition in the room [10].

3 Results

Mechanical testing consisted of a tensile and strength test and a Rockwell hardness test. The microstructure analysis consisted of three types of tests, i.e. a metallurgical test, scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX). Graphs of the average tensile strength and percentage of elongation are shown in Figures 1 and 2 respectively.

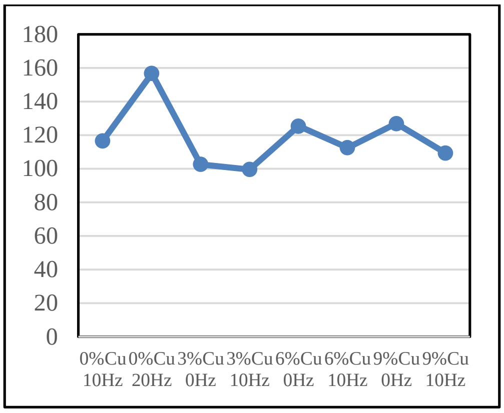

Figure 1 Ultimate tensile strength (MPa) of each specimen.

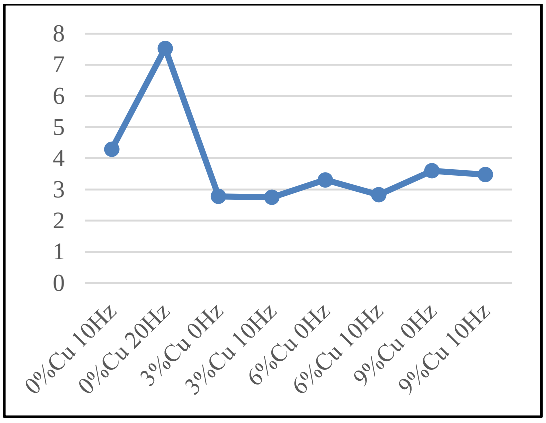

Figure 2 Percentage of elongation (%) of each specimen.

Based on Figures 1 and 2 it can be seen that the pattern of the graph was the same respectively for tensile strength and the percentage of elongation for each specimen tested. Before we analyzed the effect of the copper contents on the casted LM6, we observed the pattern in the graph for 0%wt of copper with 20 Hz of mechanical vibration; the result was much higher than for the samples with copper addition.

Eight casted alloy specimens were tested for different criteria with a Rockwell hardness machine. Five readings were taken for each specimen in a random area of the surface of the specimen to obtain the average value of the hardness readings. The scale of hardness used was HRB with a 100-kgf load. Figure 3 shows the average of hardness for every percentage of copper. It shows that 9% copper had higher hardness with normal casting than with vibration casting.

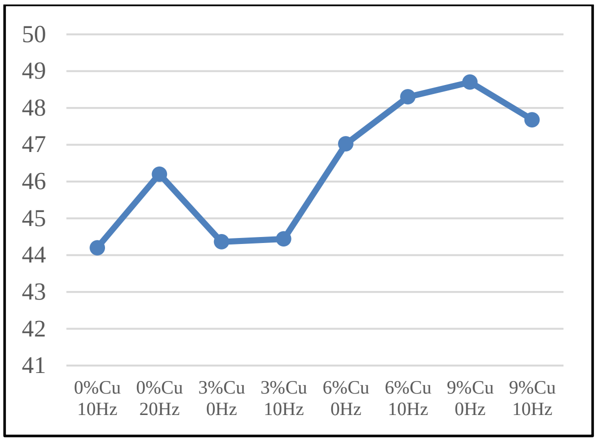

Figure 3 Graph of average Rockwell hardness (HRB).

After the specimens were put in a resin mount, grinding and polishing was done using a polishing machine to make sure that the microstructure of the samples could be observed clearly by using an optical microscope. Figures 4, 5 and 6 show the microstructures of the samples with addition of 0%wt Cu and 9%wt Cu for different vibration molding frequencies. A higher vibration frequency produces a finer structure.

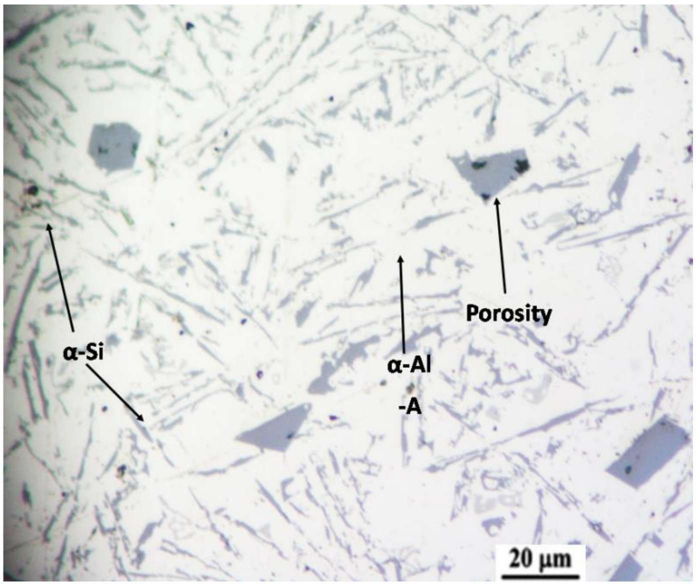

Figure 4 Magnification of LM6 with 0%wt Cu, 10 Hz of mechanical vibration.

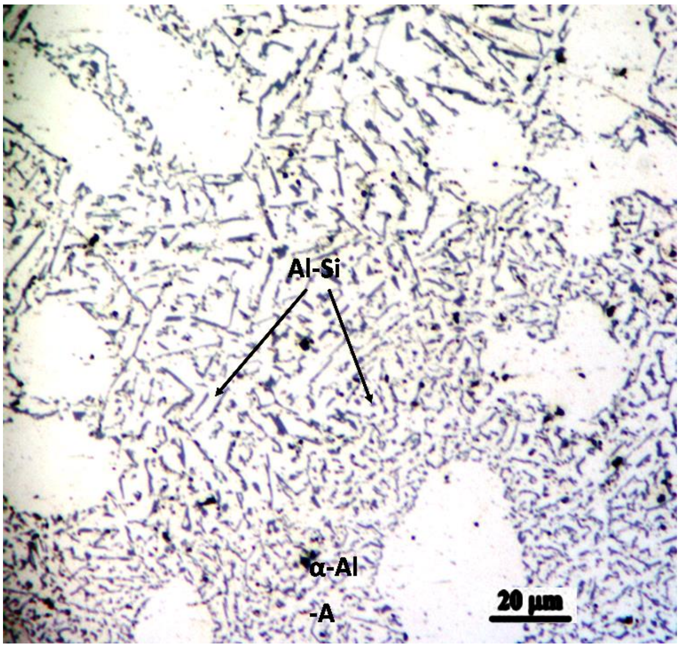

Figure 5 Magnification of LM6 with 0%wt Cu, 20 Hz of mechanical vibration.

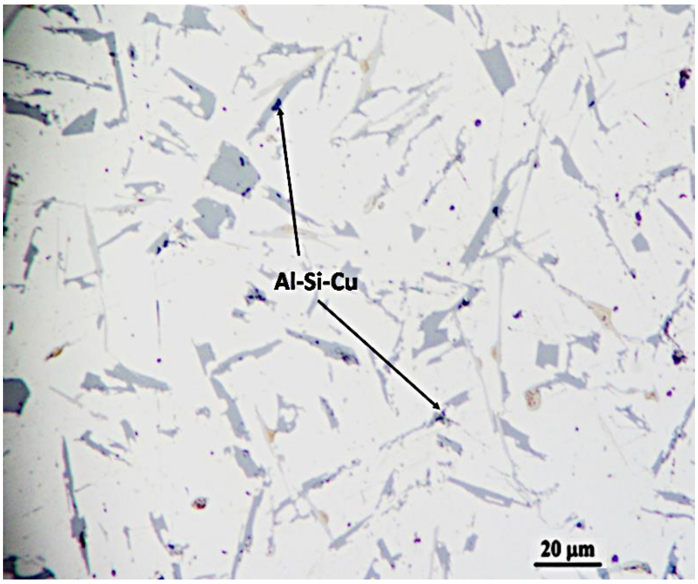

Figure 6 Magnification of LM6 with 9%wt Cu, 0 Hz of mechanical vibration.

Detailed images of all alloy specimens, except the specimen with 0%wt copper, were captured by SEM and were analyzed by energy dispersive X-ray spectrometry. Figure 7 shows the EDX analysis of the elements contained in the LM6 with addition of 9%wt Cu and 0 Hz of mechanical vibration.

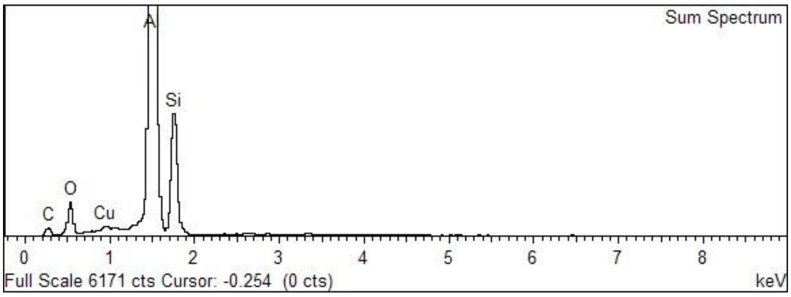

Figure 7 EDX analysis of elements contained in LM6 with 9%wt Cu and 0Hz of mechanical vibration.

It shows that at this percentage, EDX had a higher chance to detect radiation emitted by the copper. Based on the mechanical testing result, the casted LM6 added with 9%wt of copper had slightly better mechanical properties, especially the specimen fabricated without mechanical vibration molding.

4 Discussion

Based on a previous study, the tensile strength of pure LM6 casted without mechanical vibration molding had a reading of 129.71 MPa. In Figures 1 and 2 we can see that the pattern in the graph was the same for the tensile strength and the percentage of elongation for each specimen tested. Before we analyze the effect of copper contents in the casted LM6, we observe the pattern in the graph for the 0%wt copper sample with 20Hz of mechanical vibration: the results were much higher than for any sample with copper addition.

The higher tensile strength and percentage of elongation of the sample with 20 Hz of mechanical vibration molding may have occurred because the microstructure of the Al-Si was eutectic phase, meaning it was homogenous and the finest compared to the other specimens [11,12]. Mechanical vibration molding with a higher frequency produced a good quality alloy, with few defects such as cavities and porosity. The LM6 casted with 3%wt of copper, both with and without mechanical vibration molding, had the lowest percentage of elongation and tensile strength because of the low percentage of copper content. A higher percentage of copper in LM6 produces better mechanical properties, but, unexpectedly, mechanical vibration molding at 10 Hz did not affect the results very much. Based on the results of the LM6 casted without copper and with vibration molding at 20 Hz, very good results can be expected from combining the addition of copper with more than 20 Hz of vibration molding.

The graph in Figure 8 shows a significant increment of hardness with the addition of copper and mechanical vibration.

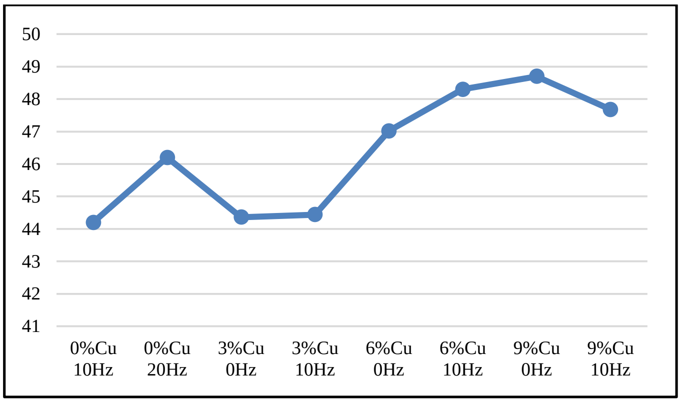

Figure 8 Graph of average Rockwell hardness (HRB).

The LM6 specimen with 0%wt of copper and mechanical vibration molding at 10 Hz had the lowest average hardness reading at 44.20. Pure LM6 with mechanical vibration molding at 20 Hz topped at 46.20, i.e. higher than the alloy with 3%wt of copper for both types of molding. This shows that a higher frequency of mechanical vibration molding leads to finer grains, which helps to decrease the chance of porosity forming inside the alloy, which can affect its hardness [13,14]. This strongly indicates that there was an effect of the copper on the hardness value, which kept increasing until the specimens reached 9%wt of copper with mechanical vibration molding at 0 Hz. On the other hand, the same copper content with mechanical vibration molding at 10 Hz had slightly lower hardness, ending up in third place. This may have occurred because even though copper addition and vibration molding when alloying LM6 is good, it also makes the structure more brittle, resulting in poor hardness. This is possibly caused by the turbulent flow of the molten mass while pouring it into the mold [15].

By observing Figures 4 and 5, even with only a 10-Hz difference in the frequency for mechanical vibration molding, there were huge differences between the specimens in terms of grain refinement and size. The LM6 specimen with vibration molding at 10 Hz showed that most of the grains were elongated, while a few silicon particles were still large in size. The LM6 specimen casted without copper and with mechanical vibration at 20 Hz showed silicon grains that were smaller compared to those in Figure 5. It had better grain refinement and arrangement, achieving excellent chemical bonding with the aluminum. It was proven in the previous mechanical tests that grain size and arrangement affected the result of tensile strength, percentage of elongation and hardness.

The specimens with addition of 9%wt of copper showed more copper but with a smaller size, both with and without mechanical vibration molding. Based on the sample's mechanical test results, the LM6 casted with 9%wt of copper without vibration molding had the best mechanical properties among all the LM6 specimens added with copper. Unfortunately, this was not as high as for the non-modified LM6 specimen with mechanical vibration molding at 20 Hz. When 9%wt of copper is combined with mechanical vibration molding at 20 Hz, a finer grain arrangement and smaller grain sizes are expected and the alloy will have higher tensile strength, hardness and percentage of elongation.

The results from the tensile test and the Rockwell hardness test show that an higher amount of copper added to LM6 leads to improvement of its mechanical properties. A higher frequency of mechanical vibration molding and percentage of copper affect the grain size and arrangement, while reducing defects such as cavities and porosity inside the alloy, hence improving its mechanical properties.

5 Conclusion

Based on the analysis of the data and findings from this study, some conclusions can be drawn. Al-Si-Cu was fabricated based on two different casting processes, namely vibration and non-vibration casting. Mechanical and microstructural analysis were carried and it was found that the optimum copper amount added to LM6 was 9%wt of copper without mechanical vibration. However, LM6 without copper addition and with mechanical vibration molding at 20 Hz had better results in terms of mechanical properties and macrostructure compared to the other specimens with a lower mechanical vibration frequency and more copper addition. This means that a higher frequency of mechanical vibration enhances the quality of the casting. In addition, the mechanical properties and grain refinement of the material were improved when the percentage of copper was increased. The best mechanical properties of casted LM6 were produced with copper addition at 9%wt and without mechanical vibration molding.

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