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Impacts of melt holding temperature on properties of the aluminum–copper–cullet metal composite

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ABSTRACT

The aluminum–copper–cullet (Al–Cu–CP) metal composite was fabricated at three different holding temperatures (800°C, 900°C, and 1,000°C, respectively) using the stir casting method. The composite was fabricated from Al, Cu, and CP. The holding temperature was varied in order to ascertain the optimum temperature for the fabrication of the composite. The Al–Cu–CP metal composite fabricated was characterized by checking its physical and mechanical properties in order to ascertain its potentials and application. The Al–Cu–CP metal composite fabricated at 800°C exhibited the best properties as the properties of the composite fabricated at 900°C and 1,000°C were relatively inferior. Thus, 800°C is the optimum holding temperature for the fabrication of the Al–Cu–CP metal composite using the stir casting method.

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1. Introduction

The fundamental subject of this research centers on the fabrication and characterization of the physical and mechanical properties of recycled Al–Cu–CP metal composites. Composite materials function mechanically as a single unit. Ordinarily, in a composite material, a hard phase material, which is the reinforcing agent, is embedded in a soft ductile matrix. The hard phase increases the strength and modulus of the composite and the soft phase acts as matrix material (Bhat and Mahesh, 2014). Usually, these two major components of composites accomplish different roles: a strong, stiff reinforcement provides the strength and rigidity which is disseminated, and in the second material, the matrix in return serves to bind and protect the reinforcements (Ahamed et al., 2016). Composites are usually manufactured to persuade proper mechanical properties that cannot be obtained from the traditional monolithic materials. This is because the composites can easily be modified to fit a particular shape or behavior. Composite materials are regarded as one of the most sophisticated and flexible engineering materials known at the moment. Composites are being used significantly for high-performance applications, for instance, in aircraft engines and, in the recent times, in the automotive industry (Hashmi, 2015; Jacob et al., 2016; Senapati et al., 2014; Sijo and Jayadevan, 2016).

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The need for light metal continues to increase, particularly for structural, automotive, and aviation industries. Aluminum is a lightweight metal with high corrosion resistance, high tenacity, and a low melting point that are commonly employed in many industries. The mechanical performance of aluminum is still low, making its applications restricted. Numerous studies were carried out to improve the mechanical properties of aluminum. In the past, increasing the strength of aluminum was carried out by adding various alloys (Syahid et al., 2020). Particulate reinforced Aluminium metal matrix composites (AlMMCs) have transpired due to the need for lightweight and high stiffness materials which are required in various applications, principally automobile products such as engine piston, cylinder liner, brake disk/drum, etc. (YC and Shankar, 2012). Understanding the behavior of Metal matrix composites (MMCs), particularly Al MMCs, is fundamental in order to know their strength, prospects, and limitations. Density is an essential factor in the study when characterizing the properties of composite materials. It is among other important parameters which determine the mechanical, tribological, and machinability properties of composite materials (Nuhu, 2017). Hardness is a mechanical property that is defined as local resistance to plastic deformation like surface indentation or scratches. Hardness is an essential feature of the composite material. The test of hardness is simple and inexpensive; it is a non-destructive and its results are readily available immediately after the test is conducted (Efzan et al., 2016; Rajaravi et al., 2019; Srivastava et al., 2016). Grain refinement could essentially improve the mechanical properties of MMCs, in terms of strength and plasticity. Additionally, the grain size strengthening efficiency was reported to have improved properties of many alloys and composites. Therefore, it is always important to obtain good grain structures to desire the attributes of engineering materials in order to suit targeted applications (Peng et al., 2018). It is also an established fact that the hardness of MMCs depends on grain size, so the lesser the grain size the more closely the particles get packed, which improves the hardness of the materials (Rana et al., 2016).

2. Materials and Methods

2.1. Preparation

The Al composites were fabricated from unreinforced Al, Cu pieces, and CP. The reinforcement materials (Cu and CP) were added in the ratio of 1:1. The metal matrix (unreinforced Al) was placed in a furnace, in a steel crucible, at a temperature of 800°C in an electric furnace. After the unreinforced Al got melted, reinforcement materials were separately added, i.e., preheated Cu pieces and CP, and stirred thoroughly. The furnace temperatures selected for the casting process were 800°C, 900°C, and 1,000°C, with successive intervals of 100°C. The lowest holding temperature was 800°C and it was chosen because the Al scrap does not give a good melt below that temperature. Similarly, 1,000°C was chosen as the highest holding temperature to see if there could be improvements due to the high temperatures, although the melting point of Al is 660°C. The Al–Cu–CP metal composites fabricated at the three different temperatures were examined and analyzed for the optimum holding temperature.

Table 1. Sample denotations for Al–Cu–CP composite with variable holding temperatures.

S/No	Temperature (°C)	Denotation
1	800	C-800
2	900	C-900
3	1,000	C-1000

2.2. Density measurement

Composites' samples fabricated at three different holding temperature of 800°C were tested for their respective densities in order to examine the effect of holding temperature on the densities of the composites. The densities of the composites were measured using the density measuring instrument from Mettler Toledo.

2.3. Microhardness test

Hardness measurement was carried out by using Vickers hardness tester. Samples from both the matrix and the composites fabricated were cut to the desired size and ground with abrasive papers of different grit sizes ranging from 240 to 1,000. Three indentations were made at random points on each sample and the average was recorded. From each group, three samples were tested and also an average was taken to represent the hardness value of that particular group of samples. The analysis was conducted based on the American Society for Testing and Materials (ASTM) E-92-17/ISO 6507-1 (2011). The commonest unit of Vickerss hardness test is represented as Vickers pyramid number (HV).

2.4. Microstructural analysis

The microstructural analysis of the samples was conducted with the guidance of the ASTM E-1382 standards for metallurgical samples' preparation. The etching process of the samples was carried out as described under the "chemical compositions analyses" section. The specimens of Al–Cu–CP composites of the treated and untreated composites and the matrix from the chemical analyses were polished using the standard metallographic technique. The specimens were then etched with Kroll's reagent. The etched specimens were then subjected to scanning electron microscopy and optical microscopy to examine their microstructures (Mohanavel et al., 2017).

2.5. Grain size analysis

A metallurgical optical microscope was employed to investigate and understand the behavior of materials based on their microstructures and microconstituents. Among these structures are the grains and grain boundaries, and their effects on the material behavior. In this technique, a small portion of the Al–Cu–CP metal composite material was prepared through a detailed procedure. The prepared sample was then examined using a metallurgical optical microscope based on visible incident light. The most popular and accurate method of measuring grain size is the ASTM E-1382 method, in which the grain size number G is defined by: $n = 2^{G-1}$, where n is the number of grains per square inch on a polished and etched material surface at a magnification of 100× and G is an integer termed as the ASTM grain size number. This expression shows that the lager the number, the smaller the grains. The grain size analysis is conducted by means of software called "iD solution". The software is built to calculate the grain number in accordance with ASTM E112 standard. The specific ASTM method used in this grain size analysis is the grain intercept method.

3. Results and Discussion

The following subsections are a series of investigations on the effects of different holding times on the properties of Al–Cu–CP composites in order to determine the most suitable holding temperature for the fabrication of the composite.

3.1. Density measurement

The Al–Cu–CP metal composites were measured for density test and the results for the density measurements were recorded as shown in Figure 1. The highest density measured was 2.890 g cm^{-3} for C-900 while the lowest was 2.818 g cm^{-3} for C-1000 and 2.820 g cm^{-3} was observed as the density value for 800°C. It is obvious that the differences between the measured values were infinitesimal to draw a conclusion from.

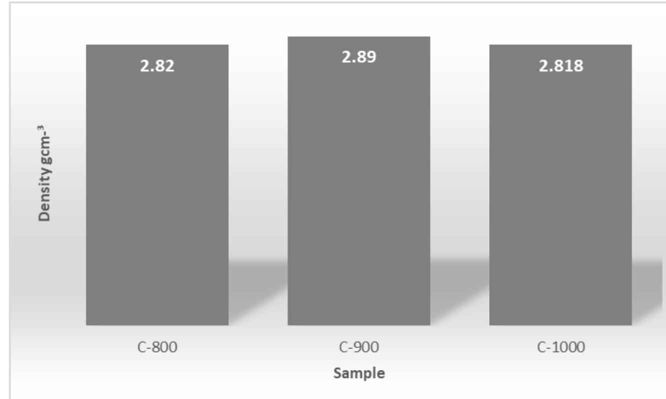

Figure 1. Effect of holding temperatures on density values.

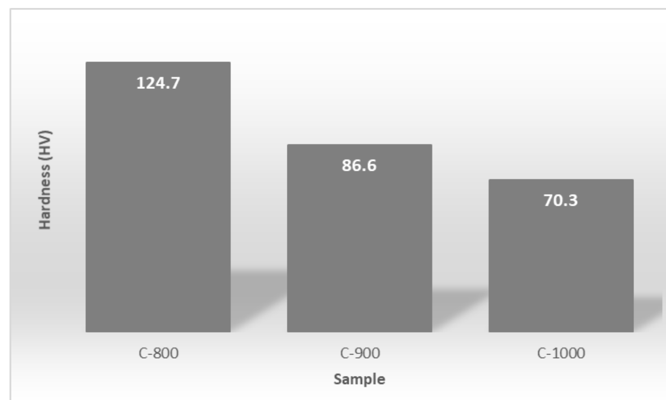

Figure 2. Effect of holding temperatures on hardness values of Al–Cu–CP metal composites.

3.2. Hardness analysis

The Al–Cu–CP metal composites were fabricated at different holding temperatures: 800°C, 900°C, and 1,000°C, while the percentage composition and melt holding time were kept constant at 20 wt. % and 60 minutes, respectively. It could be easily observed that the average hardness values decrease as the holding temperature kept on increasing. Thus, 800°C was the lowest holding temperature at which the composite was fabricated, but it recorded the highest hardness value of 124.704 Vickers' hardness (HV). At holding temperature of 900°C, the hardness value decreased to 86.613 HV and to 70.278 HV at 1,000°C, as shown in Figure 2. Usually, when composites reach their optimum peak with respect to holding temperatures, the hardness values of the composites start diminishing as a result of excessive heating. Similar observations were reported by earlier researchers (Pezda, 2014; Yusuf, 2017).

The inhomogeneity and agglomeration of the reinforcement particles in the Al matrix may be attributed to the low viscosity caused by excessive heating at higher temperatures (Tash and Mahmoud, 2016). Another factor noteworthy is the influence of temperature on the viscosity of the molten metal matrix during the stir casting process. An increase in temperature brings about a decrease in the viscosity of a molten metal which has already reached its melting point. Consequently, changes in the viscosity of the molten Al matrix influence the distribution of the reinforcement particles in the matrix. At the highest viscosity with the lowest temperature (800°C), the geometric contact of particles was regulated by a vortex of molten metal during stirring.

Therefore, the reinforcement particles were uniformly dispersed. On the other hand, when the temperature gets higher (at 900°C and 1,000°C), the viscosity gets lower and is unable to restrict the movement of the reinforcement particles by the vortex of the molten Al matrix. This leads to agglomeration and weakening of interface bonds. As a result of the excessive increase in holding temperature, the viscosity of the molten matrix decreased and weakened the overall strength of the material. This observation is in agreement with the findings reported by Sozhamannan et al. (2012). Rajaravi et al. (2019) earlier reported a decline in the hardness of the Al composite when the melt holding temperature was increased from 820°C to 840°C.

3.3. Microstructural analysis

The surface morphology of the Al–Cu–CP composites fabricated at the three different holding temperatures, 800°C, 900°C, and 1,000°C are shown in Figure 3. Section 3.2 has shown that the temperatures at which the composites were produced have impacts on the hardness of the composites. The Al–Cu–CP metal composite produced at 800°C was found to have the highest hardness value than the other two composites which were produced at higher temperatures. The decline in the hardness of the composite at higher holding temperatures could be due to the weakening and rupture of the grain boundaries as shown by the red circles in Figure 3. The higher temperatures have weakened and ruptured the grain boundaries. These defects could further be attributed to a decrease in viscosity of the Al melt as a result of the high holding temperatures.

This leads to the agglomeration of the reinforcement material and voids within the grains. Therefore, the tendency for the reinforcement particles to agglomerate or porosity occurrence is high when the holding temperature is higher than necessary. Sozhamannan et al. (2012) reported similar observations. The traces of the boundary weakening could be spotted, although not significant, from the Scanning electron microscope (SEM) micrograph of C-800 in Figure 3. The ruptures and cracks become more visible as the temperature increases. This manifestation has been highlighted and shown in Figure 3 (a)–(c) with the enlargement of each micrograph at a magnification of 1,500×. The SEM micrographs indicated the locations of the incomplete interface bonds as red circles. Many incomplete interface bonds were observed at the surface of C-900 and C-800. This finding further substantiates the reason for decrease in hardness value of the material. Excessive heating at high fabricating temperatures is another reason for the defect; as shown in Figure 3(a), a similar observation was reported by Canakci and Varol (2014). Therefore, it is evidently clear that the Al–Cu–CP metal composite fabricated at 800°C better has distribution and bonding between the Al matrix and the reinforcement materials. The surface morphology of C-800 looks better and more homogeneous. This is why the hardness value C-800 appeared to be higher than the rest of the compositions.

3.4. Grain size

Still, in line with microstructure analysis, the effects of holding temperature on the grain size of the Al–Cu–CP composites fabricated at different temperatures were investigated and the findings are presented in Table 2. The grain size kept on increasing as the holding temperature increased, consequently reducing the *G*-number values. This is due to the fact that material expands with an increase in energy. Ahmad et al. (2017) reported a similar observation. The materials' grain sizes have an inverse relationship with their hardness property. That is, as the grain size decreases, the hardness of the composite increases and vice versa. This is because of the close packing of the reinforcement particles (Rana et al., 2016).

From Table 2, it is clear that C-800 has the finest grain size, while C-1,000 has the coarsest grain size. This could be one of the reasons why C-800 has superior properties over the other two composites' compositions. It could also be justified by the combined effects of grain coarsening and the occurrence of some micro-cracks and pores, which leads to the weakening of the composite material, especially at a longer excessive melt holding temperature. This is in agreement with findings reported by Tash and Mahmoud (2016). Kumar and Birru (2017) also suggested that grain refinement helps to achieve enhanced mechanical as well as tribological properties of the composite

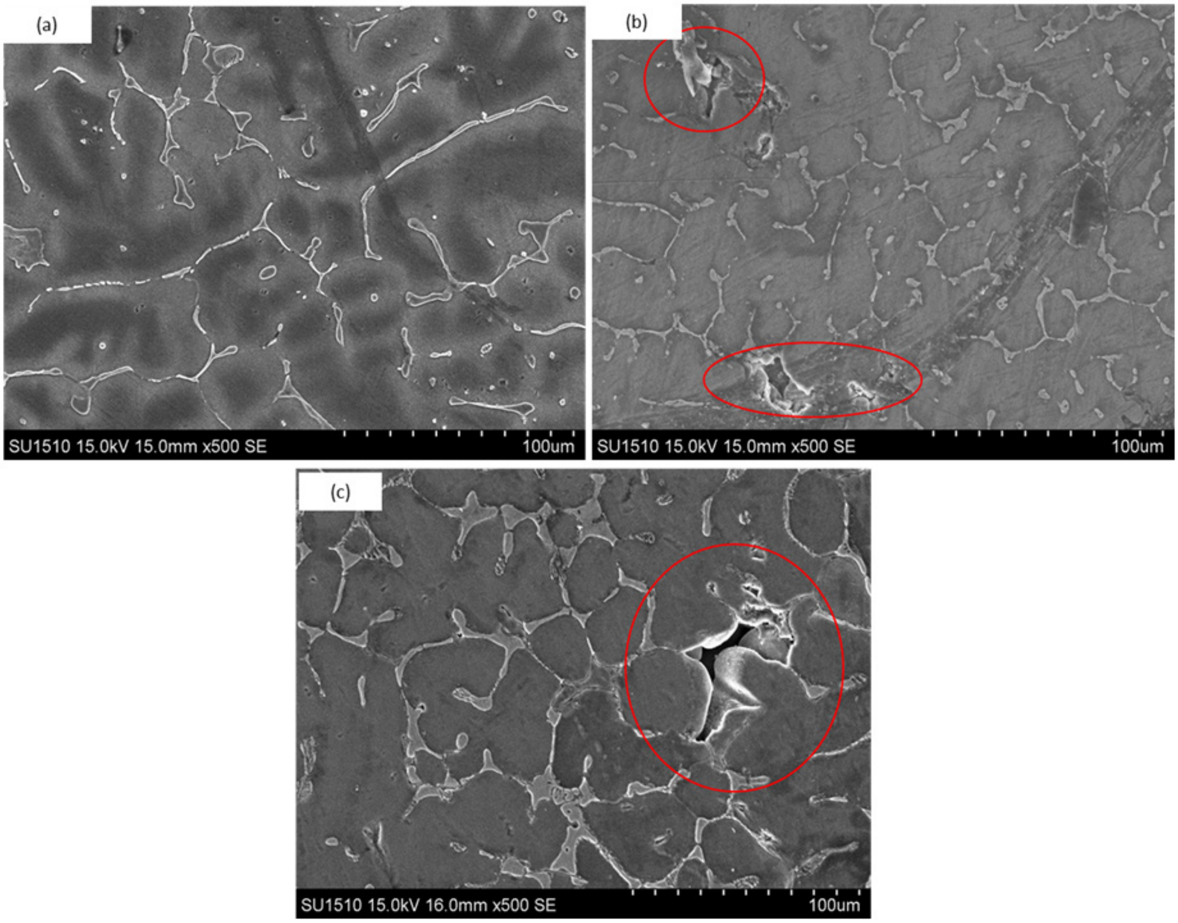

Figure 3. Microstructure of the Al–Cu–CP metal composite at holding temperatures of (a) 800°C, (b) 900°C, and (c) 1,000°C, at magnification of 1,500×.

Table 2. Effect of holding temperatures on the grain size of Al–Cu–CP metal composites.

Holding temperature (°C)	Number of intercepts	Mean intercepts	*G*-number
800	707	93	10.36
900	460	87	9.10
1,000	321	63	7.60

materials. The authors also confirmed that the hardness increased with a decrease in the average grain size of Al composites in their study on the response of the addition of bamboo leaf ash to Al matrix using the stir casting method. This assertion has been further stressed by Syahid et al. (2020) who stated that lower holding temperatures give rise to smaller grain and subsequently high strength material is obtained while higher holding temperatures result in bigger grain sizes which are of low strength.

4. Conclusion

According to the analyses carried out on fabrication of Al–Cu–CP metal composite on different holding temperatures, 800°C, 900°C, and 1,000°C, it evident that the 800°C holding temperature is the optimum for the fabrication of Al–Cu–CP metal composite because the composite exhibited the best properties when fabricated at that temperature. Therefore, it could be concluded that the composite has the optimum composition of Al–Cu–CP metal composite as well as melt holding time and holding temperature.

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