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MECHANICAL PROPERTIES OF ALUMINUM ALLOYS PRODUCED USING DIFFERENT STIR-CAST STIRRING RATES

AUTHORS:
O. Adigun[1,*], A. A. Aribisala[2], A. R. Adigun[3], S. O. Olusunle[4], O. O. Ajibola[5], A. F. Owa[6], A. D. Isadaro[7], C. I. Madueke[8], I. E. Abegunde[9], and K. B. Omonubi[10]

AFFILIATIONS:
[1,2]Department of Mechatronics Engineering, Federal University Oye-Ekiti, Nigeria.
[3]Department of Industrial Chemistry, Federal University Oye-Ekiti, Nigeria.
[4]Engineering Materials Development Institute, Akure, Nigeria.
[5,6,8,9,10]Department of Materials and Metallurgical Engineering, Federal University Oye-Ekiti, Nigeria.
[7]Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria.

***CORRESPONDING AUTHOR:**
Email: oluwole.adigun@fuoye.edu.ng

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Abstract

In this study, we examined how different stir casting stirring rates affected the mechanical properties of aluminum-copper (Al-Cu) alloys. Al-Cu alloys were cast and developed utilizing an electromechanical stir casting technique with stirring rates ranging from 0-90 revolutions per minute (rpm), and the alloys had Cu compositions of 0–15 wt. % (weight percent). The microstructural evolution was investigated using an advanced optical microscope. When the developed alloy materials were evaluated for microhardness and tensile strength, it was found that the raise in composition of copper and increase in stirring rate led to progressive improvements in microhardness while changes observed with the tensile strength were obviously indeterminate. The mechanisms responsible for the changes seen are also described.

1.0 INTRODUCTION

Advancements in science and technology require the creation of innovative engineering materials for a variety of engineering applications, particularly in areas where lightweight and improved mechanical properties are of importance (e.g., aerospace, marine, machine part fabrication, etc.). These areas require strong materials that may be produced by the development of composite or alloy materials. Over the years, aluminum metal matrix composites have been widely useful for the development of lightweight components with specialized end-use applications [1]. In light of this, various aluminum metal matrix composites have been produced over the years with various improved mechanical properties [2], [3].

Haripriya *et al*., investigated the addition of titanium to pure aluminum [2]. They concluded that the introduction of fine grains of titanium into the aluminum crystals led to a reduction in the boundary displacement of the composite produced. In a related development, the effect of copper reinforcement on mechanical properties was studied in a binary Al-Cu (aluminum and copper) alloy system. Improvement in the mechanical characteristics observed was linked to copper atoms' reinforcement [4]. Usually, the choice of reinforcement in a composite is promulgated by the possession of unique properties related to the purpose for which the composite material is being developed.

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Moreover, studies on strengthening aluminum alloys using copper (Cu) atoms have received a lot of attention recently, with promising results and applications mostly in the aerospace industry [4], [5].

Besides the improvement in mechanical properties of aluminum via the alloying technique, modifications of the processing technique have also been adopted over time. For instance, attempts have been made by a number of researchers to optimize the stir casting process and assess the effects of the modified parameters (e.g., stirring speed, stirring duration, etc.) on mechanical properties [6], [7]. Sharma *et al.*, optimized the stir casting process using four levels of stirring speed and stirring duration variations to develop Al-SiC composites with improved wear resistance [7]. Research investigations that employ the stir casting process for the production of alumium alloys have been on the rise in recent years [8], [9]. However, studies that attempt to optimize the stir casting process (via variations in experimental factors like stirring speed, stirring duration, stirring temperature, etc.) are still rare to come by.

In essence, more studies capable of providing information on how the various stir casting process parameters could be manipulated to facilitate improved material properties would be a welcome development. Over the years, the rheocasting technique for the production of aluminum alloys, which was first created at MIT (Massachusetts Institute of Technology) in the early 1970s, has led to a variety of research outcomes [10]. Aside from some aluminum alloy development, however, the stirring technique is also applied in other material production processes. For instance, stirring is employed at various phases of the steelmaking process to aid in homogenization, stimulate alloy dissolving, encourage deoxidation, improve degassing, and eliminate inclusions [11].

A recent study that examined how the stirring approach affected macrosegregation and crystal appearance in continuously cast steel slabs showed that stirring the samples produced refined crystals, and metallographic studies of the steel slabs revealed that refining the crystals through the stirring process also improved macrosegregation [12]. Another contemporary application of stirring in metallurgy is called FSP (friction stir processing). The FSP uses strong localized plastic deformation to enhance the alloy's surface qualities by stirring a selected tool through the specimen to create a finer grain microstructure [13], [14]. Therefore, stirring has a lot of possibilities for material development as a processing method.

This study will explore the intriguing relationship between stirring speed and the mechanical properties of a cast aluminum-copper alloy. Through a combination of experimental investigations, microstructural analysis, and mechanical testing, this study endeavors to contribute to the existing body of knowledge on alloy development and processing. The investigation delves into how the manipulation of stirring speed during the alloy's production process might impact its final mechanical characteristics. By systematically varying stirring speeds (i.e., 0 rpm, 10 rpm, 50 rpm, and 90 rpm) and analyzing the resulting mechanical properties, this study seeks to uncover valuable insights that could potentially enhance the performance and applicability of this alloy in various engineering applications. Ultimately, the insights gained from this research could pave the way for the design and fabrication of Al-Cu alloys with improved mechanical performance, further expanding their range of applications across various sectors of engineering and manufacturing.

2.0 METHODOLOGY

The metals utilized in this project were purchased locally from Science Commodities in Lagos, Nigeria. A weighing balance (Wenser HPB-high precision balance) was used to determine the composition ratio of copper and aluminum prior to melting. The Al-Cu alloy is heated in a crucible furnace to melt between 660 °C and 1100 °C depending on the weighted composition, and then the melt is poured into a ladle with varied rates of agitation. An independent in-line torque meter that was positioned between the stirring rotor and the drive motor during the design of the stirring procedure allowed for rheological measurements.

This arrangement also makes it possible to control the temperature gradient within the ladle. In order to allow the metal to solidify spontaneously without the use of artificial cooling agents, the molten metal was tapped from the furnace into a ladle, which was then placed in a stirring machine to swirl the material at various speeds of 0 rpm, 10 rpm, 50 rpm, and 90 rpm before pouring into the ready sand molds. 16 samples were obtained, ranging from sample A1 to sample A16, as indicated in Table 1. This technique produced four unique samples for each stirring rate. Before being machined into a shape appropriate for testing, the cast Al-Cu alloy material was shaken out of the sand mold using a vibrating machine.

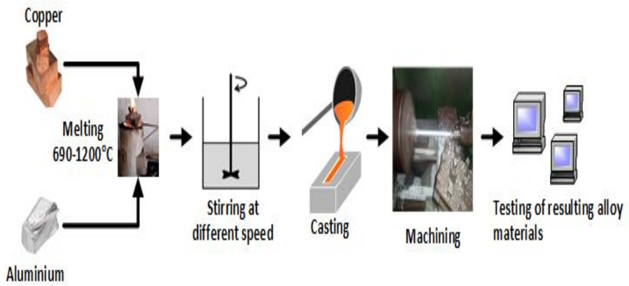

Figure 1: Flow diagram of the stir casting process

The mold was first heated to drive off all potential moisture before molding in order to prevent flaws like porosity, shrinkage, and swelling. A suitable quantity of molten metal was also poured into the whole mold cavity as rapidly as possible to prevent anomalous solidification. In order to achieve steady solidification during stirring, casting was done before the highest melting point of the composition was really reached.

The samples' optical micrographs were analyzed to disclose the microstructure of the created substance. With a crosshead speed of 5 mm/min, advanced universal testing equipment was used to conduct tensile tests at room temperature. A 100 gf load was applied during the Vickers microhardness test using automated (electric) equipment. The indenter was released from the lever after placing the sample's surface on the anvil of the hardness tester and making an indentation with a dwell period of 15 seconds before touching the sample. The test was repeated three times, and the mean value was reported.

Table 1: Stir cast parameters and alloy compositions

Samples label	Cu composition (wt. percent Cu)	Stir cast rate (rpm)
A1	0	0.0
A2	0	10.0
A3	0	50.0
A4	0	90.0
A5	5	0.0
A6	5	10.0
A7	5	50.0
A8	5	90.0
A9	10	0.0
A10	10	10.0
A11	10	50.0
A12	10	90.0
A13	15	0.0
A14	15	10.0
A15	15	50.0
A16	15	90.0

3.0 RESULTS AND DISCUSSION

Figures 2–5 display the microhardness and ultimate tensile strength of aluminum alloy materials manufactured with various wt. percents of copper and various stirring speeds. It was found that the increase in copper composition and the increase in stirring rate led to progressive improvements in microhardness, while changes observed in tensile strength were obviously indeterminate. Some mechanisms affect these mechanical characteristics. They include stirring effects, precipitation hardening, and solid solution hardening. Stirring led to the spread of Cu atoms throughout the structure of the alloy. Precipitation hardening occurred by the precipitation of extra Cu dissolved in the alloy solution. The solid solution hardening occurred by the dissolution of the alloying Cu atoms in the alloy solution. Additional information about these mechanisms is provided below.

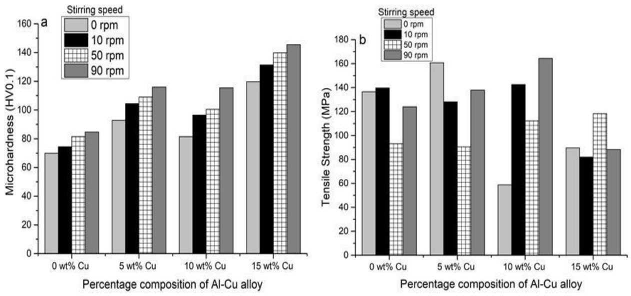

Figure 2: Effect of different stir cast stirring rate on the mechanical properties (a) Microhardness (b) Tensile strength.

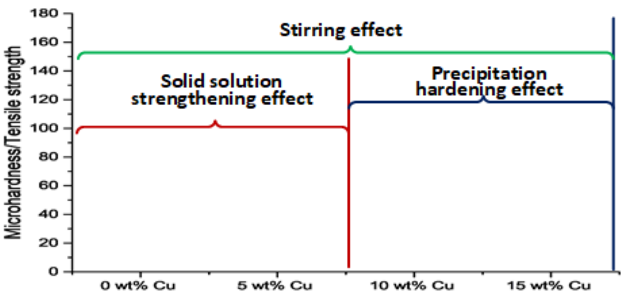

Figure 3: Illustration of the mechanisms leading to observed change in mechanical properties

3.1 Stirring Effect

By altering the in situ grain boundary arrangement, which may lessen grain boundary diffusion, the stirring process alters both the grain boundary chemistry and structure. This has an impact on the tensile strength and microhardness of Al-Cu alloys for the various Cu compositions (see Figure 2). It is found that the stirring procedure aided in the dispersion of Cu atoms in the Al solution, contributing to the suppression of plastic deformation in addition to having an impact on the mechanical characteristics of the final Al-Cu alloys by minimizing grain boundary diffusion. Consequently, a progressive increase in microhardness was seen with an increase in stirring rate for Al-Cu compositions with 0 wt. percent to 15 wt. percent Cu (Figure 2a). The tensile strength measurements, however, did not correspond to a faster stirring rate (see Figure 2b). This could be caused by a number of things, including the manufactured

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samples' various degrees of internal defects like cracks and porosity. Given that each sample may experience different degrees of internal mixing as a result of the stirring procedure, it appears that these flaws cannot be completely ruled out. This shows that tensile strength is mostly dependent on bulk samples, whereas hardness is a gauge of a material's resistance to surface deformation.

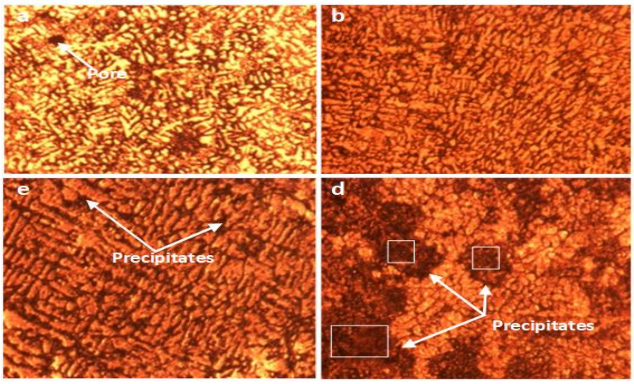

Figure 4: Optical images (x 800) of the produced Al-Cu alloys samples (a) 0 wt. percent Cu (b) 5 wt. percent Cu (c) 10 wt. percent Cu (d) 15 wt. percent Cu

3.2 Precipitation Hardening Effect

The solubility limit of a solute is the greatest amount of that solute that can dissolve in a solvent at a specific temperature. The resulting solution is saturated at this stage. Nevertheless, supersaturation happens when the concentration of the available solute exceeds the permitted solubility limit. Extra solute particles may precipitate out of solution and create a distinct precipitate phase (Figure 4). It has been determined that 5.8 wt. percent Cu is the maximum amount of Cu that may be dissolved in an Al solvent at 550 °C [15]. As a result, extra Cu atoms dispersed at high temperatures may have precipitated upon cooling, resulting in fine, dense precipitates that slow down dislocation motion and increase hardness. It appears that when too much dissolved copper leaves the Al-Cu alloy solution as a result of supersaturation, a precipitation hardening effect happens. It is discovered that the initial precipitation hardening effect for compositions containing 10 wt. percent Cu results in a minor drop in hardness (see Figure 5a). With a Cu composition of 15 wt. percent, the control of dislocation migration by precipitates was enhanced over time. The hardness of the alloy gradually increased from 10 wt. percent Cu to 15 wt. percent Cu in the region under the precipitation hardening effect (see Figure 3).

3.3 Solid Solution Strengthening Effect

Solid solution strengthening involves the purposeful addition of impurities (also known as alloying elements) that prevent dislocation migration. It has been demonstrated that solid-solution strengthening lowers stacking faults, principally resulting in resistance to dislocation slides. This is the primary deformation mode for materials with defective crystalline structures [16]. The inclusion of Cu elements is therefore expected to be the cause of the subsequent variations in the mechanical properties of the Al-Cu alloy (see Figure 5). The solubility limit of Cu atoms in an Al solvent is 5.8 wt. percent Cu at 550 °C [15]. [s]It is supposed that this solid solution strengthening occurs in the range of 5 to 10 wt. percent Cu (see Figure 3). The Cu atoms in the Al lattice operate as obstructions to dislocation migration that prevent plastic deformation along the stress field. To put it another way, the observed changes in the measured mechanical properties may have been caused by the deliberate addition of dissolved Cu to the Al solution, which made plastic deformation challenging. As a result, a concurrent rise in hardness was noted, particularly between alloy compositions of 0 wt. percent Cu and 5 wt. percent Cu, as shown in Figures 5a–d.

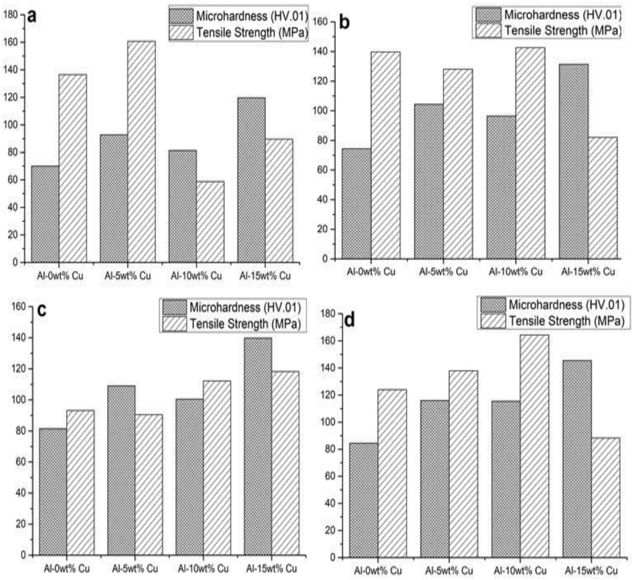

Figure 5: Mechanical properties of the Al-Cu alloy materials produced at different stirring rate (a) 0 rpm (b) 10 rpm (c) 50 rpm (d) 90 rpm

The "precipitation effect" had no impact on the variations in hardness and tensile strength within this 0-5 wt. percent Cu addition range. The stirring effect, though, seems to have had an impact on this range. The alloy's hardness increased concurrently from 0 wt. percent Cu to 5 wt. percent Cu, but only for 0 wt. percent Cu did the tensile strength increase between stirring speeds of 0 rpm and 10 rpm. At the same stirring rate and 5 wt. percent Cu, a reduction was seen. The stirring procedure may have prevented dislocation movement (and consequently plastic deformation) within the structure at 5 wt. percent Cu (stirring rate between 0 and 10 rpm), which is why the loss in tensile strength at this point is not surprising.

4.0 CONCLUSIONS

Investigations have been done into how varying stirring speeds affect the mechanical characteristics of stir-cast Al-Cu alloys. Al-Cu alloys containing 0 wt. percent Cu, 5 wt. percent Cu, 10 wt. percent Cu, and 15 wt. percent Cu were studied at stirring rates of 0 rpm, 10 rpm, 50 rpm, and 90 rpm. The following observations have been discussed:

i. The microhardness of the generated samples continuously increased as the stirring rates were increased (see Figure 2a). The observed increase in microhardness can be due to aberrations in the in situ grain boundary arrangement and homogenous dispersion of Cu atoms in the Al solution, which obstruct grain boundary diffusion and muffle plastic deformation. As a result, a gradual increase in the microhardness of the materials can be seen as the Cu content of the Al-Cu alloy increases.
ii. However, the results for tensile strength did not agree with either the increase in stirring rates or the wt. percent of Cu (see Figure 2b). This might be because the samples during the stir-cast process had varying degrees of internal defects, such as fractures and porosity. It appears that tensile strength mostly depends on bulk samples, whereas hardness is a gauge of a material's resistance to surface deformation.
iii. The solid solution hardening caused by the Cu atoms inside the Al lattice and the precipitation hardening brought on by the supersaturation of extra Cu atoms in the Al-Cu alloy solution during the dissolution process are three mechanisms that may have contributed to the observed mechanical properties at different times.

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