

The Effects of Variable Stirring Speeds On The Mechanical Properties of Cast Aluminum Alloys

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Abstract

The influence of variable stirring speeds on cast aluminium-copper alloys and the resulting enhancements in mechanical properties have been described in this study. Aluminium-copper (Al-Cu) alloys with 0-15 wt% Cu compositions were prepared via electro-mechanical stir casting process using various stirring speeds (0 rev/min, 10 rev/min, 50 rev/min and 90 rev/min) and the alloy materials produced were tested for microhardness and tensile strength. Increase in both wt% Cu compositions and stirring speeds were observed to have led to improvements in microhardness and tensile strength. The microstructural and mechanical characterisations also revealed that improvements in material properties recorded could be attributed to three mechanisms which are: solid solution hardening, precipitation hardening and the stirring effect.

1. Introduction

Stirring is a process of dispersion in such a way as to cause mixture in a liquid or paste. It is usually done to achieve homogenous blend in the particles of two or more materials and applicable as a processing technique in the production of various materials [1]–[4]. Quite a number of research interests have resulted from the rheocasting process first developed at Massachusetts Institute of Technology (MIT) in the early 70s [5]. Though most studies in the use of stirring for the modification of material properties have been done using non metals [6]–[9], its application in the production of metallic material with improved properties is also quite prolific and advancing [10]–[13]. In the production of steel for instance, stirring is applied at various stages to promote homogenisation, enhance alloy dissolution, encourage deoxidation, improve degassing and assist in inclusion removal [14]. Fujimura and Brimacombe recently studied the influence of the stirring process on the macro-segregation and crystal morphologies of continuously cast steel slabs [15]. They found that the stirred fraction resulted in refined crystals and metallographic examination of the steel slabs revealed that refinements of crystals led to improvement in macrosegregation. Furthermore, the influence of stirring on solid solution strengthening leading to improvement in microhardness of a cast aluminium alloy has equally been presented in a latest study [14]. Another recent application of stirring in metallurgy is the friction stir processing (FSP) where strong localized plastic deformation is used to improve the surface properties of an alloy by the stirring motion of a designated tool through the specimen in order to produce finer grain structure and microstructural modification [16], [17]. Practically, stirring – as a processing technique- offers great potential for materials development.

On the other hand, recent trends in the production of new classes of aluminium (Al) alloy materials have continued to rise in order to meet the demand of making more reliable material properties needed for various applications [18], [19]. Al alloys series are metallic materials produced when elements such as copper (Cu), iron (Fe), magnesium (Mg), tin (Sn), silicon (Si), zinc (Zn) and manganese (Mn) are added to pure Al in percentage compositions between 0-15 wt% (with minute presences of other elements) in order to improve material quality with unique properties. Relatively, studies into improvement of aluminium alloy properties by reinforcement with copper (Cu) atoms have been widely examined with promising

outcomes and applications mostly in the aerospace industries [20], [21]. For instance, in a study to examine the mechanical behaviour of binary Al–Cu alloy where 0–10 wt% Cu particles were used to reinforce the metal/metal composite by Reddy and his research team, improvement in mechanical properties observed were attributed to the presence of the copper reinforcements and its kinetics of hardening [21]. In addition to this, a lot of research studies on Al-Cu alloys geared towards the development of useful and improved material properties have been published using conventional methods of casting or powder metallurgy in the material production processes [22]–[24]. Furthermore, probes into the mechanisms responsible for the resultant improvements in material properties have been helpful in the design of the various alloys invented to ensure production continuity [25]. Production of Al alloy materials using innovative modifications in processing techniques could, therefore, be explored for possible advanced properties development.

This study would examine the effects of stirring on the mechanical properties of Al-Cu alloys using different stirring speeds for the dispersion of the Cu atoms in the Al solution for possible advancements in material properties. The study would also harness the improved materials properties transformation achievable in Al-Cu alloys using various wt% Cu compositions in the development of novel materials with unique properties for useful engineering purposes. The mechanisms responsible for the ensuing changes in mechanical properties (i.e. microhardness and tensile strength) produced would also be examined to complement future design of related materials.

2. Methodology

The metal components utilised for this work were sourced locally. Before the melting process, percentage compositions of the aluminium and copper were measured using weighing balance. Depending on the weighted compositions, the Al-Cu alloys are heated until melting takes place between 660 °C and 1100 °C in a crucible furnace before the melt is tapped into a pouring ladle where stirring takes place at various rotating speeds. The stirring process was designed to make use of an independent in-line torque meter that was placed between the stirring rotor and drive motor to enable rheological measurements. The arrangement also enables control of the temperature gradient within the pouring ladle. The molten metal was tapped from the furnace into a pouring ladle which was then placed on the stirring machine in order to stir the content at different speeds before pouring into the prepared sand moulds and allowed to solidify naturally without any artificial cooling effect. This process produces four different specimens for each stirring speed and sixteen samples labelled S1 to S16 were produced as shown in Table 1. Vibrating machine was used to shake off the cast Al-Cu alloys materials from the sand moulds before machining the specimens using lathe to produce shapes suitable for the testing stage.

In order to prevent defects such as porosity, shrinkage and swelling, the moulds were first preheated before casting so as to remove any moisture contents present. Also, abnormal solidification was prevented by ensuring that enough molten metal was poured to fill the entire mould cavity and the pouring process was done as fast as possible. Hence, the pouring was done before the actual melting

point of the metal with the highest melting temperature in the composition was attained in order to allow for stable solidification over the stirring process.

Optical micrographs of the samples were investigated so as to reveal the microstructures of materials produced.

The tensile test was conducted at room temperature using an advanced universal testing machine at a cross-head speed of 5 mm/min.

The Vickers microhardness test was done using an automatic (electric energy source) machine at a load of 100 gf. The surface of the specimen was positioned on the anvil of the hardness tester before releasing the indenter from the lever until it touches the specimen to produce indentation with a dwelling period of 15 s. The tests were repeated three times and the average values reported.

Table 1
Compositions and stirring speed for materials production

Samples label	Alloy composition	Stirring speed (rpm)
S1	100% Al	0
S2	100% Al	10
S3	100% Al	50
S4	100% Al	90
S5	95%Al + 5%Cu	0
S6	95%Al + 5%Cu	10
S7	95%Al + 5%Cu	50
S8	95%Al + 5%Cu	90
S9	90%Al + 10%Cu	0
S10	90%Al + 10%Cu	10
S11	90%Al + 10%Cu	50
S12	90%Al + 10%Cu	90
S13	85%Al + 15%Cu	0
S14	85%Al + 15%Cu	10
S15	85%Al + 15%Cu	50
S16	85%Al + 15%Cu	90

3. Results And Discussion

Results of hardness and ultimate tensile strength tests carried out on the aluminium alloys materials produced with varying wt% Cu compositions and at various stirring speeds are presented in Figures 2-5. Three mechanisms are believed to influence the mechanical properties observed. These include the stirring effect which causes dispersion of the Cu element within the Al lattice; precipitation hardening effect resulting from precipitation of excess Cu solute in the Al solution; and the third mechanism is the solid solution effect caused by the dissolution of the alloying Cu solute in the Al solution. These mechanisms are further buttressed in the subsequent paragraphs.

Stirring effect

The stirring process distorts *in situ* grain boundary arrangement which changes both the grain boundary chemistry and structures by filling vacancies with the Cu atoms to reduce grain boundary diffusions. This in turn influences the Al-Cu alloy microhardness and tensile strength across the various Cu compositions (see Figure 2); encompassing the region explicit to both solid solution and precipitation effects (Figure 3). Besides its effect on the resulting mechanical properties of the Al-Cu alloy via reduction in grain boundary diffusion, the stirring process was also observed to have aided dispersion of Cu atoms in the Al solution and contributed to inhibition of plastic deformation. These combined effects may have caused hardness of the alloy materials to increase progressively with increase in the stirring speed (across 0 rev/min, 10 rev/min, 50 rev/min and 90 rev/min) for each compositions of the 0 wt%- 15 wt% Cu, as shown in Figure 2a. However, changes in tensile strength as a result of the stirring process aren't consistent with increase in the stirring speed (see Figure 2b).

Precipitation hardening effect

The maximum amount of solute dissolved in a solvent at a given temperature is the solubility limit of the solute; and at this point the resulting solution becomes saturated. However, supersaturation occurs when the available solute concentration is higher than the acceptable solubility limit which results in the precipitation of excess solute particles from the solution and may form separate precipitate phases (Figure 4d). The solubility limit of Cu solute in Al solvent at 550°C has been shown to be 5.8 wt% Cu [26]. Hence, any excess Cu atoms which may have possibly dissolved at higher temperature could be precipitated on cooling, creating fine, closely packed precipitates that retard dislocation motion to improve hardness and alter the tensile strength. Apparently, the precipitation hardening effect occurs when excess Cu solute comes out of the Al-Cu alloy solution due to supersaturation. Conversely, it was observed that the initial precipitation hardening effect around 10 wt% Cu composition experiences a slight drop in hardness as compared with resulting hardness from the solid solution strengthening effect which occurs at around 5 wt% Cu (see Figure 5a). In the long run, inhibition of dislocation motion produced by the precipitates improved at 15 wt% Cu composition. Similar to changes in mechanical properties observed in the compositions under solid solution strengthening effect, there was a progressive increase in hardness of the alloy from 10 wt% Cu to 15 wt% Cu in the region under the precipitation hardening effect (see Figure 3); a relative drop in tensile strength (particularly at 0 rev/min) was also observed between the compositions under the solid solution strengthening effect (5 wt% Cu)

and initial Cu solute precipitation (10 wt% Cu) before further improvement in tensile strength at 15 wt% Cu (0 rev/min, see Figure 5b). This relative drop may be due to the fact that only few Cu precipitate particles were initially available to impede plastic deformation as the tensile strength increased with possible rise in Cu precipitates at 15 wt%. In a related study, reduction in tensile strength was equally observed between 5 wt% Cu and 10 wt% Cu in an Al-Cu alloy [27]. It was also observed that further changes in the tensile strength due to precipitation hardening effect (at stirring speed above 0 rpm) becomes clearly unpredictable and further studies (beyond the scope of the current one) may be required to understand these developments.

Solid solution strengthening effect

Solid solution strengthening is a strengthening approach which is achieved by deliberate additions of impurities (i.e. alloying elements) that act as hindrance to dislocation movement. Solid solution strengthening has been revealed to have ability to reduce the stacking fault energy in crystal lattice of alloys, leading mainly to resistance of dislocation cross slip- which is the primary mode of deformation in imperfect crystalline materials [28]. Hence, the resulting change in matrix strength and microhardness of the Al-Cu alloys produced (see Figure 5) is believed to be partly due to the addition of soluble Cu element which may have distorted the atomic lattice of the material to restrain dislocation movement – and causing changes to the tensile strength and hardness of the alloys produced; as similarly discussed in a previous publication [13]. This effect is considered to have taken place in the region below 10 wt% Cu (see Figure 3); since the solubility limit of Cu atoms in Al solvent have been shown to be 5.8 wt% Cu at 550°C [26]. Within the Al lattice, the Cu atoms act as a barrier to dislocation movement and makes plastic deformation along the stress fields difficult. In other words, deliberate addition of Cu solute to the Al solution may have led to difficulty in plastic deformation resulting in the changes observed in the mechanical properties tested. Therefore, simultaneous increase in hardness was particularly noticed from 0 wt% Cu to 5 wt% Cu alloy compositions as revealed across Figure 5a-d. Within this range of 0-5 wt% Cu addition, changes in the hardness and tensile strength was not influenced by the “precipitation effect”; however, the stirring effect appears to have affected this range. While there was concurrent increase in hardness of the alloy from 0 wt% Cu to 5 wt% Cu, tensile strength only increased for 0 wt% Cu between 0 rev/min and 10 rev/min stirring speed but a decrease in tensile strength noticed within same stirring speeds at 5 wt% Cu. The decrease in tensile strength at 5 wt% Cu (between 0 rev/min and 10 rev/min stirring speeds) is not unexpected because the stirring processes may have caused dispersion of barriers to dislocation movement (and in turn plastic deformation) arising from the spreading of Cu atoms within the alloy crystal lattice.

4. Conclusions

Effect of Cu composition in Al-Cu alloy and stirring speed variation on the mechanical properties of cast aluminum alloys has been characterized. Mechanical properties were improved via increase in Cu solute compositions from 0 wt% to 15 wt% in the Al solution as well as increase in stirring speed (from 0 rpm to 90 rpm) which was adopted to disperse the Cu solute in the pool of Al lattice. Improvement in mechanical

properties recorded is attributed to three mechanisms which are: Solid solution hardening effect, precipitation hardening effect and stirring effect. The solid solution hardening effects were noticed at 0 wt% and 5wt% Cu; and the precipitation hardening effects were observed at 10 wt% and 15 wt% Cu; while the stirring effects influenced mechanical properties across 0-15 wt% Cu composition. Increase in the stirring speed led to a progressive increase in microhardness but changes in tensile strength was quite irregular. The solid solution hardening effect also led to expected increases in microhardness but inconsistent changes in tensile strength between 0 wt% and 5 wt% Cu compositions -across the stirring speeds examined (i.e. 0 rev/min, 10 rev/min, 50 rev/min and 90 rev/min). In the same vein, the precipitation hardening effect observed between 10 wt% and 15 wt% Cu also resulted in anticipated increases in microhardness across the stirring speeds but changes in tensile strength were incoherent.

Declarations

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Code availability: Not applicable

Ethics approval: The authors confirm that this article has not been submitted before for publication elsewhere and the content is original.

Consent to participate: The authors confirm participation as main, corresponding or co-authorship to publish this article

Consent for publication: The authors confirm agreement to publish this article if accepted for publication

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Figures

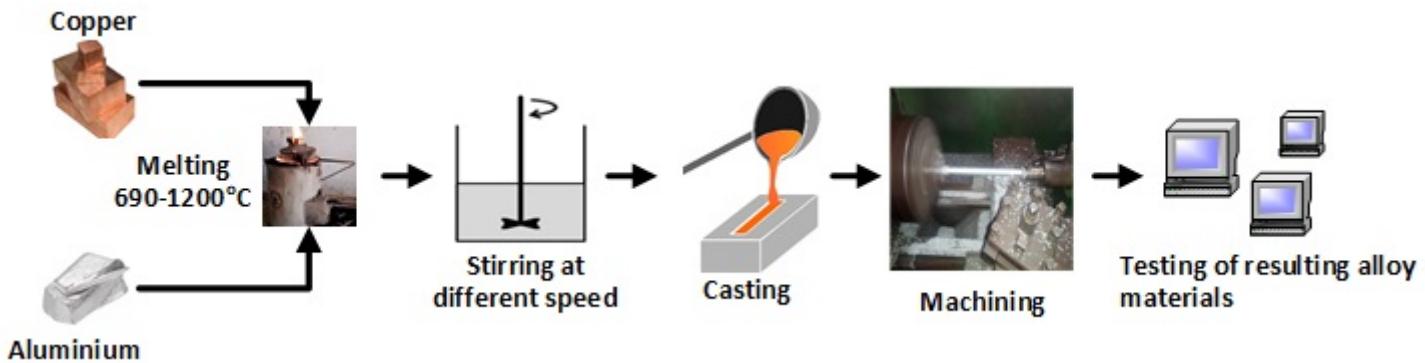


Figure 1

Schematic design of experiment

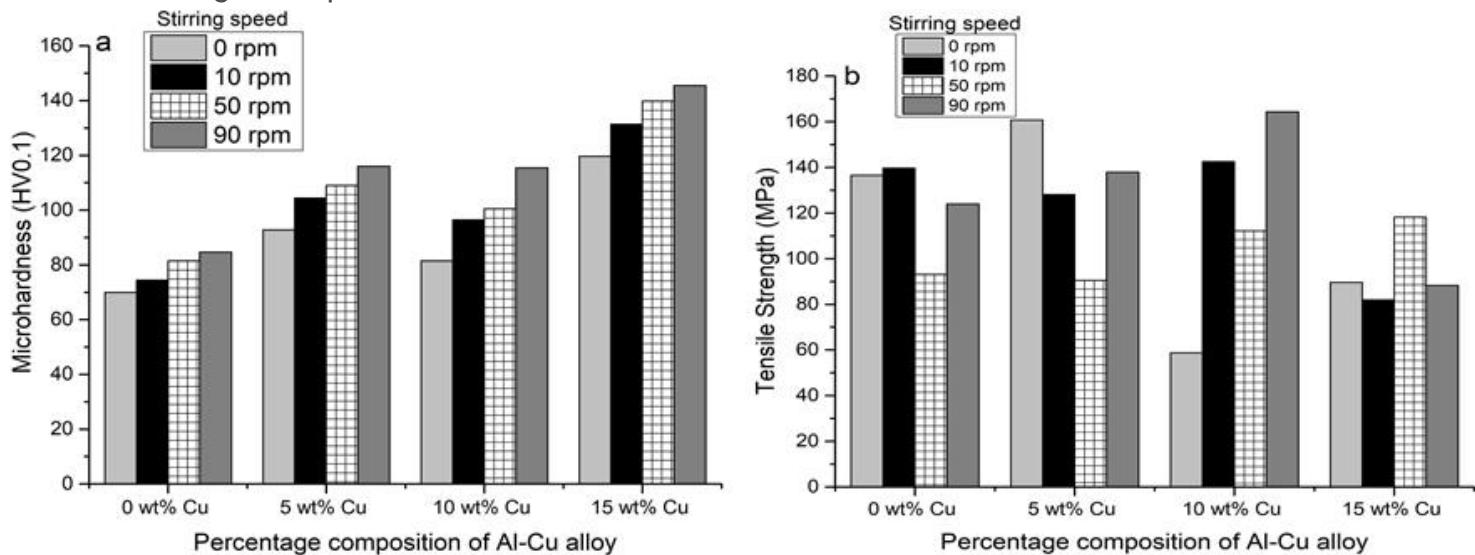


Figure 2

Effect of stirring on mechanical properties (a) Microhardness (b) Tensile strength: (rpm = rev/min)

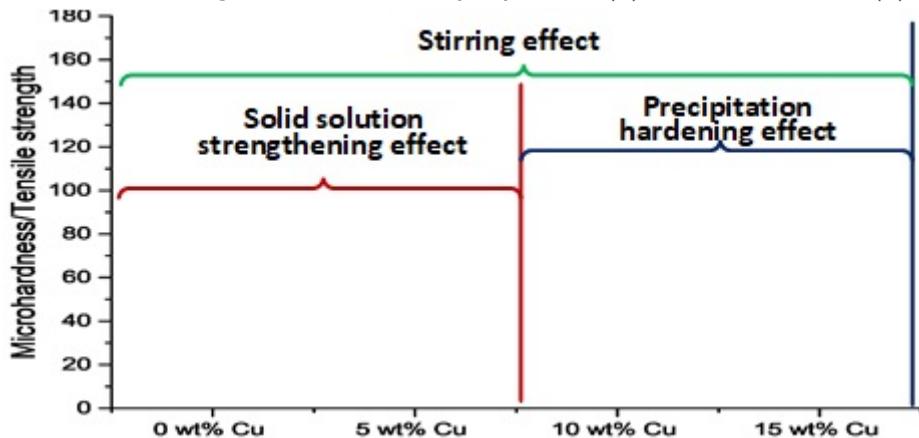


Figure 3

Mechanism leading to changes in mechanical properties.

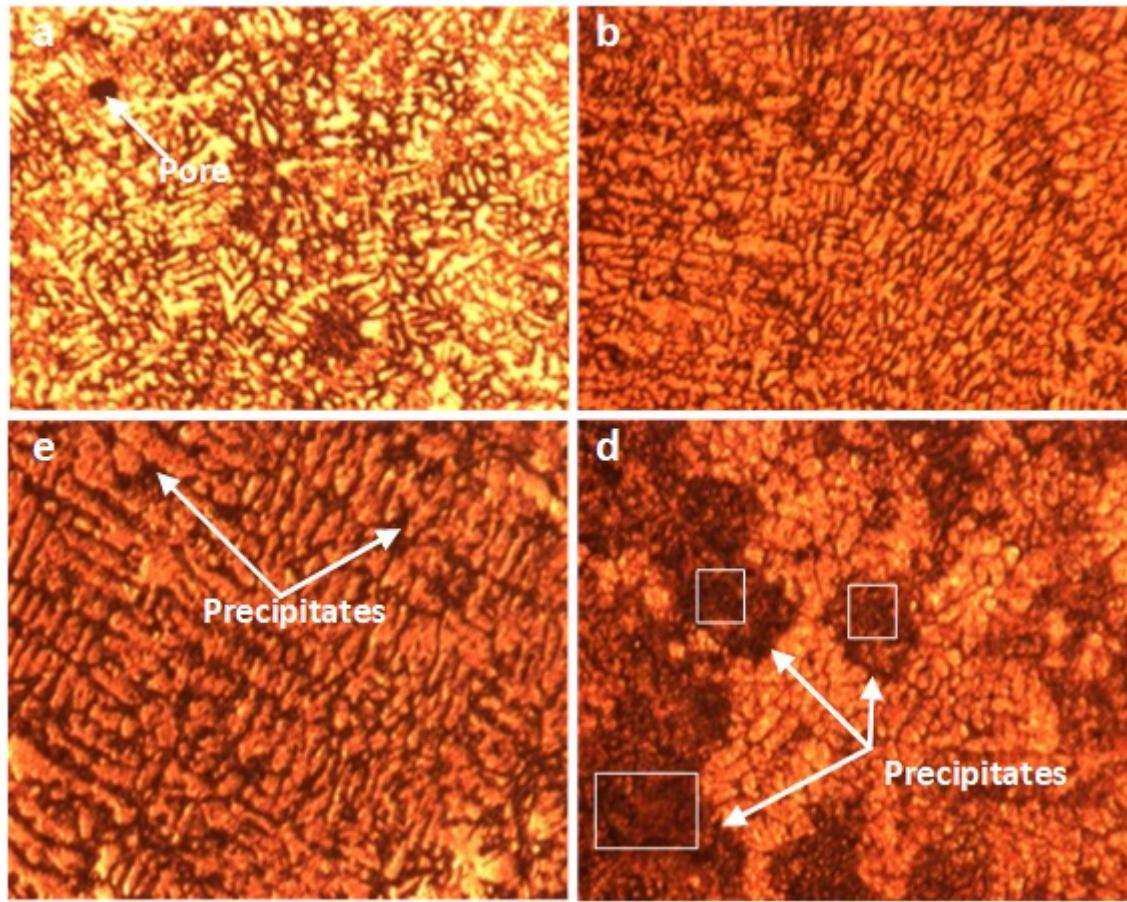


Figure 4

Optical images of resulting Al-Cu alloys: x 800 (a) 0wt% Cu (b) 5 wt% Cu (c) 10 wt % Cu (d) 15 wt % Cu

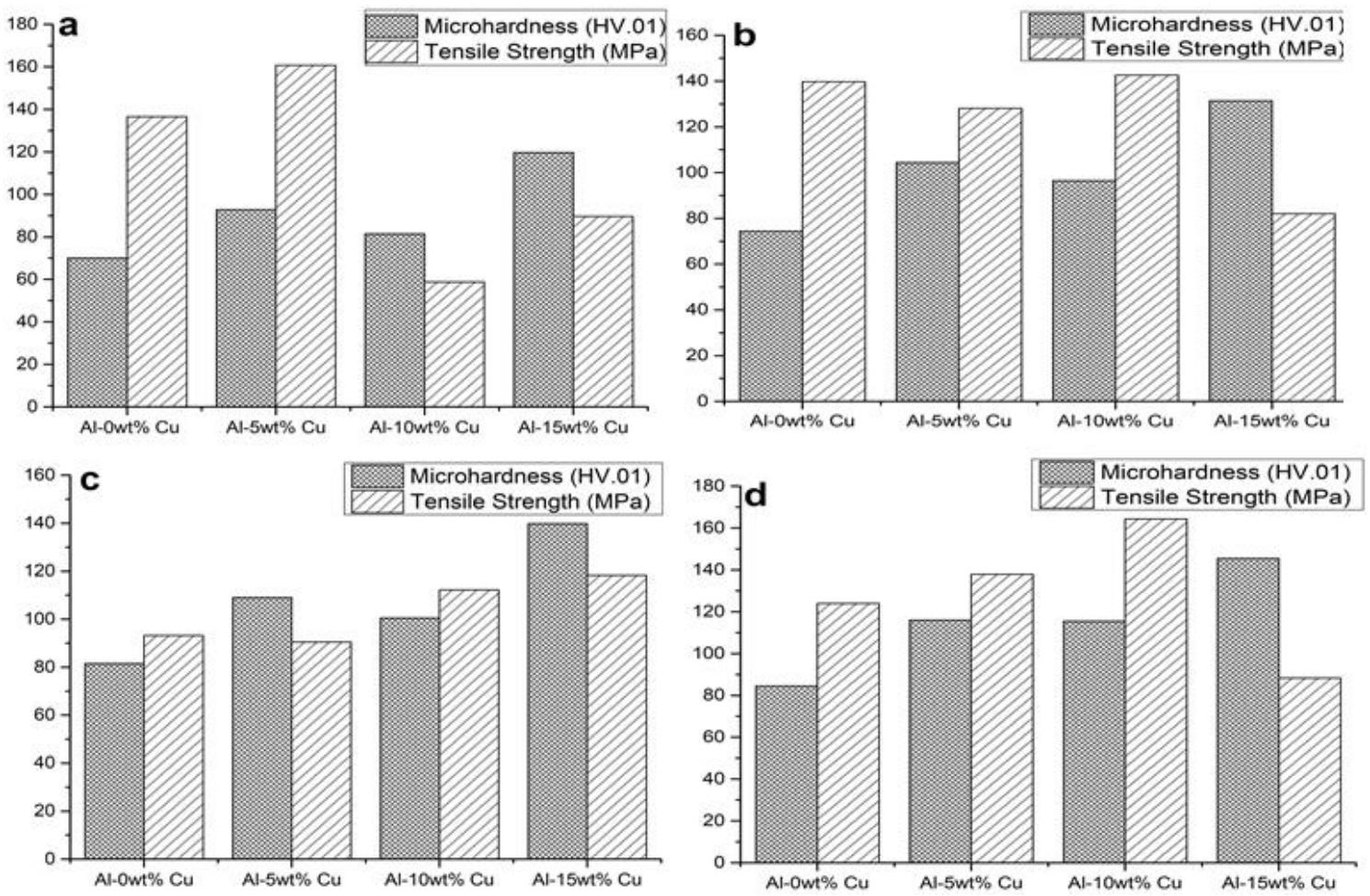


Figure 5

Hardness and Tensile Strength of the Al-Cu alloy materials produced at different stirring speed (a) 0 rev/min (b) 10 rev/min (c) 50 rev/min (d) 90 rev/min

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