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Mechanical properties and microstructure of precipitation-hardened Al-Cu-Zn alloys

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ABSTRACT

Many automobile components are made from aluminium and its alloys because of their suitable properties. Metals and their alloys are usually subjected to heat treatment in order to improve their properties. Thus, the effect of precipitation hardening on the mechanical properties and microstructure of sand cast aluminum alloys was investigated. The cast Al-Cu-Zn alloy samples were heat-treated at 460 °C for 2 hours, quenched in water and then age-hardened at 160 °C for 5 hours. Tensile, impact and hardness tests were carried out on the heat-treated and the as-cast Al-Cu-Zn alloys samples. The surface morphology of both the as-cast and the precipitation hardened samples was observed using digital metallurgical microscope. The ultimate tensile strength of the precipitation hardened samples A2 (81.2Al: 1.56Cu: 8.33Zn) and B2 (81.7Al: 3.25Cu: 6.16Zn) are 173.42 N/mm^2 and 168.02 N/mm^2, respectively. These values are higher than those of the as-cast samples A1 and B1, which are 168.02 N/mm^2 and 157.84 N/mm^2, respectively. The precipitation hardened Al alloy samples also displayed higher hardness, impact energy and elongation than the as-cast samples, indicating improved properties. The presence of coarse reinforcing intermetallic phases was observed in the as-cast samples as compared to the well-distributed fine grain size microstructure of intermetallic phases in the precipitation hardened samples. It can be concluded that precipitation hardening improves the mechanical and microstructure properties of aluminum alloys and thus will find wider applications in automobile industries for the production of components and parts.

Keywords: Al-Cu-Zn alloy; automobiles; precipitation hardening; mechanical properties; microstructure.

INTRODUCTION

Aluminum has since been identified as the most common metal on earth, forming about eight percent of the earth's crust. It is the third most abundant element known to man and it can respond well to forming operations, making it useful in various applications [1, 2]. These include production of domestic appliances, chemical reactions and storage bottles, vessels and containers, buildings, bridges, packaging foils, aircrafts, ships and automobile components and parts, etc. Aluminum is used for a variety of applications due to its light weight, good thermal and electrical conductivities, good heat and light reflectivity, its [3-

5]non-rusty nature, non-toxicity, as well as attractive appearance and recyclability [6]. Based on its light weight, Al has become a material that is most sought after in the automobile industry. It has been established that a 24% weight reduction is achievable with aluminum alloy part as compared to a similar steel part [7, 8]. Automobiles with higher aluminum components and parts will consume lesser fuel and thus lead to lower CO_2 emission as a result of their lighter weight [9]. The ability of recycling 90% of the parts made from aluminum alloy is another key reason for its continuous growth in the automobile industry. Aluminum can be used to build car bodies and fabricate parts such as hubcaps, engine block, radiators, chassis and many more. Intricate and larger zones can also be developed with Al and its alloys without corresponding weight penalties. Aluminum has a unique combination of properties, which makes it relevant even for other engineering and structural works [10, 11]. However, relatively low strength and unstable mechanical properties are some of the drawbacks for its application as a structural material, and these can be improved through alloying and heat treatment. Coherent precipitate, which interfere with dislocations, are formed in aluminum matrix when alloyed or heat treated and this improves the mechanical properties [12]. However, the formability of aluminum alloy may be hindered by the presence of relatively brittle intermetallic compounds, which can induce damage and premature failure during a wide variety of sheet forming and bending operations [13, 14]. These alloys are also susceptible to stress corrosion cracking [15, 16] due to their non-homogeneous nature and inherent residual stresses associated with their fabrication methods [17]. These drawbacks can be eliminated through appropriate heat treatment operations. Thus, the aim of the present study is to prepare Al-Cu-Zn alloys through sand casting process and determine the effect of precipitation hardening on the samples.

EXPERIMENTAL SET UP

Materials

Aluminum, copper wire and zinc scraps were purchased from a local scrap shop within Ilorin, Kwara State, Nigeria. The scraps were weighed using electronic weighing balance prior to charging into the furnace.

Chemical Composition Analysis of the Materials

Table 1 shows the weight percentage of different elements present in the prepared sample specimens labeled A and B.

Table 1.Weight percentage of different major elements in the melted Al-Cu-Zn alloy specimens.

Elements	Sample A (wt %)	Sample B (wt %)	Elements	Sample A (wt %)	Sample B (wt %)
Al	81.2000	81.7000	Mg	0.0010	0.0880
Cu	1.5600	3.2500	Cr	0.0024	0.0081
Zn	8.3300	6.1600	Ni	0.0010	0.0670
Si	1.8000	2.0800	Ti	0.8000	0.0110
Fe	1.7800	0.4900	P	0.0031	0.0036
Mn	0.0096	0.0740	Pb	0.0410	0.1800
			V	0.00310	0.0016

Test Samples Preparation

Two different test samples were prepared with varying compositions of Zn and Cu. Each of the compositions was separately placed inside a crucible prior to melting in the furnace. To cast Al-Cu-Zn alloys, Zn was melted first because of its lowest melting temperature compared to Al and Cu, followed by Al and then Cu. The highest furnace temperature was 1110°C based on the melting temperature of the metals while the total melting time was about 90 minutes. The casting procedure involves fabrication of wooden patterns, making green sand mould, melting of the scraps using a muffle furnace and pouring of the molten melt into the prepared mould. After pouring, cylindrical shaped samples of length 150 mm and diameter 15 mm were allowed to solidify and then cooled at normal room temperature. The samples were then machined into the various standard shapes and dimensions for the chemical compositional and microstructural analyses, hardness, and the impact tests. The tensile test specimens (Figure 1) were prepared according to British Standard BSEN 10002-1[18].

After machining, one sample each of different composition was taken to the crucible furnace for heat treatment. The samples were heated at 460 °C for 2 hours in a muffle furnace as shown in Figure 2. This was followed by quenching in water to allow for total cooling before returning into the furnace for artificial ageing at 160 °C for up to 5 hours. The samples were then returned into water for fast cooling prior to tensile, hardness and impact tests as well as microstructure analyses for the precipitation hardened samples. The final form of the precipitation hardened samples is similar to that of the as-cast samples depending on the type of tests/analysis. The tensile test specimen is shown in Figure 1.

Figure 1. Tensile test specimen.

Figure 2. Samples in furnace during heat treatment.

Experimental Procedure

Chemical composition analyses of the samples were carried out using optical light emission spectrometer (SPECTRO-06000939). This was done in order to find out the weight percentage of Al, Cu, Zn Si, Fe and other minor constituents. Tensile testing was done on a Monsanto Hounsfield tensometer (Figure 3b) in order to determine the ultimate tensile strength, the breaking strength and the percentage elongation. The hardness of the samples was determined on a Brinell hardness tester (Figure 3c) with indenter of diameter 10 mm and load 500 kg. The average diameter of indentation was measured with a portable microscope attached to the scale. Impact strength of the samples was determined using Izod impact testing machine with a V-notch at the level of the top of the clamp as shown in Figure 3d. The microstructures of the samples were examined on a digital metallurgical microscope (Serial no 0524011, Maker: Princeton, USA). This was after a series of grinding and polishing to obtain scratch-free surface. The mirror-like surface was etched in 2% Nital. This was immediately followed by washing and drying prior to viewing under the metallurgical microscope as shown in Figure 3a.

Figure 3. Experimental set up for (a) Microstructural test (b) Tensile test (c) Hardness test (d) Izod test for impact energy.

RESULTS AND DISCUSSION

Tensile Test

The stress-strain curves region labeled A is the elastic limit region, B is the ultimate tensile strength region, C is the breaking point as shown in Figure 4. The figure shows that precipitation hardened samples A2 and B2 displayed higher plastic deformation than as-cast samples A1 and B1 before the final rupture. This indicates that the precipitation hardened samples A2 and B2 became more ductile than the as-cast samples (A1 and B1) as a result of heat treatment, which resulted into the formation of intermetallic precipitates as revealed by the microstructures. Higher plastic deformation usually indicates improved ductility, resulting in ductile failure of such materials [19]. Ductile materials have wider areas of applications in automobiles, general engineering and construction industries. Thus, precipitation hardening of Al alloys will improve their applications in automobile industries. Isadare et al. [15] stated that age-hardened sample of T6 (tempered aluminum alloy series 7000) can withstand higher plastic deformation, which agrees with the observation in the present study. There is an elastic distortion as shown in Figures 4a and 4b during elastic deformation of samples A2 and B2, which may be due to the precipitation hardening effect on the atoms of the alloying elements in the Al matrix [20]. This is also in agreement with the report by Zhao et al. [19], which suggested solid solution strengthening from elastic distortion and stated that it could be as a result of substitutional atoms of Mg and Zn in aluminum matrix. As shown in Table 2, precipitation hardened samples A2 and B2 displayed higher ultimate tensile strength than the as-cast samples A1 and B1 probably due to the presence of coherent precipitate [12] and thus will have better mechanical properties. These results correspond to that obtained by Isadare et al.[18], Du et al.[21] and Kaya et al.[22], which stated that age-hardened samples have high number of grain boundaries that result in high ultimate tesile strength. It was also observed that the percentage elongation of sample A2 (2.85%) and B2 (1.83%) is higher compared to that of as-cast samples A1 (2.29%) and B1 (1.54%), indicating better ductility of the heat-treated samples. Liao et al. [23] opined that improved properties of high-pressure processed nanostructured copper may be due to grain-size effect on deformation mechanism. The increase in ductility led to increase in energy required for the movement of dislocation required to cause fracture as shown in Figure 5 where the impact energy of samples A2 and B2 surpasses the impact energy of the as-cast samples A1 and B1.

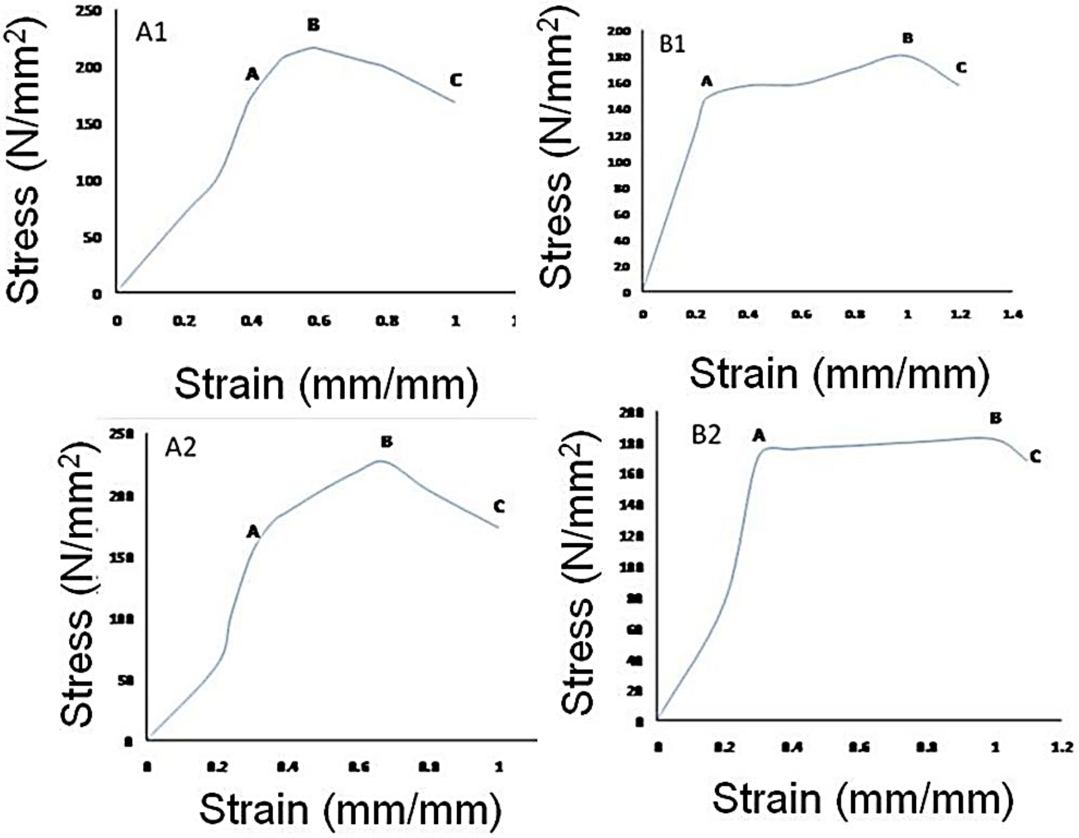

Figure 4.Stress-strain curve of the as-cast samples A1& B1 and precipitation hardened samples A2 & B2

Table 2. Tensile properties of the as-cast and precipitation hardened Al-Cu-Zn alloys.

Samples	Composition (wt. %)	Heat treatment	Ultimate tensile strength (N/mm^2)	Breaking Strength (N/mm^2)	Elongation (%)
A1	1.56wt%Cu 8.33wt%Zn 81.2wt%Al	Nil	216	168.02	2.29
A2	1.56 wt% Cu 8.33 wt% Zn 81.2 wt% Al	Precipitation hardening	226	173.42	2.85
B1	3.25 wt% Cu 6.16 wt% Zn 81.7 wt% Al	Nil	180	157.84	1.54
B2	3.25 wt% CU 6.16 wt% Zn 81.7 wt% Al	Precipitation hardening	182	168.02	1.83

Hardness Test

The result of hardness test is given in Table 3. The higher Brinel hardness (HBR) value obtained in the age-hardened aluminum alloys A2 (49.2 HBR) and B2 (64.6 HBR) as compared to the as-cast A1 (42.40 HBR) and B1 (53.4 HBR) is due to the presence of $MgZn_2$ precipitates and improved grain sizes. Isadare et al. [20] also reported that T6 aluminum alloy possessed better hardness, which was related to the presence of coherent $MgZn_2$ precipitate in the structure of the alloy sample. The result is also in agreement with previous works [24-26] that reported that age-hardened aluminum alloys with grain structures are harder and stronger compared to the as-cast alloys. The high hardness value will increase the wear and corrosion resistance of parts like the engine block, motor casings, pistons and even engine cylinders [24, 25].

Table 3.Tensile Properties of the as-cast and precipitation hardened Al-Cu-Zn alloys.

Sample	Composition (wt. %)	Heat treatment	Hardness (HBR)
A1	1.56 wt% Cu 8.33 wt% Zn 81.2 wt% Al	Nil	42.40
A2	1.56 wt% Cu 8.33 wt% Zn 81.2 wt% Al	Precipitation hardening	49.2
B1	3.25 wt% CU 6.16 wt% Zn 81.7 wt% Al	Nil	53.40
B2	3.25 wt% CU 6.16 wt% Zn 81.7 wt% Al	Precipitation hardening	64.60

Impact Test

Impact is the measure of work done to fracture [27]. The various values of the impact energy at which each specimen fractures are shown in Figure 5. Sample A1 has impact energy of 6.120 J while B1 has impact energy of 5.984 J. The heat-treated specimen A2 has impact energy of 6.392 J while specimen B2 has impact energy of 6.256 J. These results indicate that heat treatment improves the impact property of the as-cast aluminum alloy samples possibly due to dislocation movement during the precipitation heat treatment. This result agrees with the observation of Isadare et al. [20], which reported that impact energy increased as the ductility increases during age hardening of the aluminum alloy. In their work, T6 aluminum alloy under heat treatment has a percentage elongation of 15% as compared to the as-cast samples that have 11% percentage elongation.

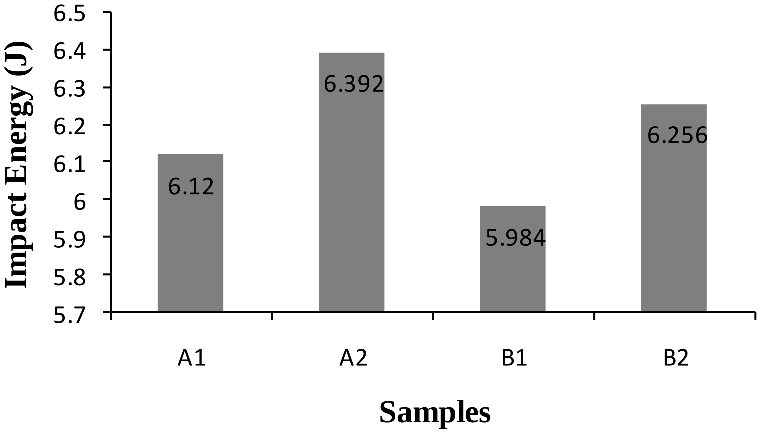

Figure 5. Impact energy of the as-cast Al-Cu-Zn alloys samples A1 and B1 compared to the precipitation hardened Al-Zn-Cu alloys samples A2 and B2

Surface Morphology

The as-cast specimen A1 in Figure 6(a) reflects a coarse precipitation of Cu and Zn clusters in the matrix with little presence of $MgZn_2$ compound along the grain boundaries. The as-cast specimen B1 in Figure 6(b) has presence of Zn and Cu clusters precipitated along the Al matrix. The presence of $MgZn_2$ precipitated around the Al, Cu clusters; the cluster indicates coarse intermetallic phase. The heat-treated alloyed specimen A2 of Figure 6(c) shows less cluster of Zn and Cu precipitated within the matrix. A well-distributed $MgZn_2$ at the grain boundaries, which reflect the effect of heat treatment on the specimen, was also observed. The matrix of the heat-treated alloyed specimen B2 in Figure 6(d) consists of essentially fine Al, Cu, Si and Fe crystals precipitations with $MgZn_2$ well-distributed at grain boundaries in the matrix, which serves as reinforcement within the specimen. The presence of dispersed precipitate of $MgZn_2$ corresponds to the results of Salamci [28] and Du et al [21]. in their report. They observed that $MgZn_2$ intermetallic phase was formed from Al-Zn-Mg-Cu alloys that were subjected to aging heat treatment. Isadare et al. also worked on the effect at As-cast cooling on the microstructure and mechanical properties of age-hardened 7000 series aluminium alloy and they reported a similar behaviour in the age-hardened samples, which showed finely dispersed precipitates of $MgZn_2$ in the aluminium matrix. This further explains the improved tensile strength of A2 and B2 over the as-cast samples, which agrees with the postulation of Li and Peng [29] that the Al-Zn-Mg alloy can obtain the highest strength level in natural and artificial aging. The uniform distribution of the Si, Cu, and $MgZn_2$ reinforcement in the Al matrix, precipitated in the heat-treated specimen, makes them better suited automobile parts, such as body work, piston and the likes, as compared to the as-cast specimens.

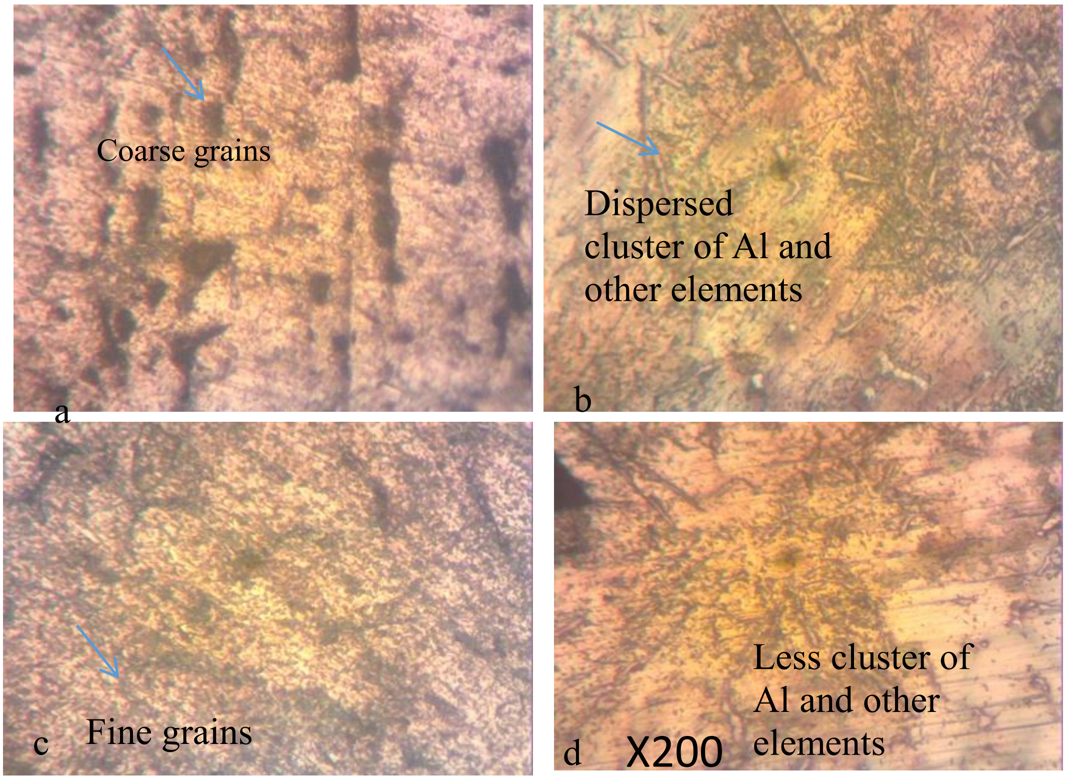

Figure 6. Micrograph of (a) as-cast sample A1, (b) B1 and precipitation-hardened sample (c) A2, (d) B2.

CONCLUSIONS

The precipitation-hardened Al-Cu-Zn alloys were found to increase in tensile strength and breaking strength with a corresponding increase in ductility. Hardness values increased in the heat-treated specimens compared to the as-cast specimens. The heat-treated specimen exhibits higher impact energy compared to the as-cast specimen. Precipitation hardening improves the mechanical properties and the microstructure of the aluminum alloys. The results have revealed that properties of Al-Cu-Zn alloys can be improved for wider applications in automobile parts such as the engine block and other areas through precipitation hardening. The effect of an increase/decrease in the percentage of Cu and Zn in aluminum under precipitation hardening can be further researched.

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