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Effect of 4%wt. Cu Addition on the Mechanical Characteristics and Fatigue Life of Commercially Pure Aluminum

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Abstract

Aluminum is widely used in many engineering applications due to its light weight. However, pure aluminum has some weakness in its mechanical properties due to its columnar microstructure with large grain size. The mechanical properties can be improved by different methods, such as cold working, heat treatment, and alloying. This study aims at enhancing the mechanical properties of commercially pure aluminum through the addition of 4% wt. copper. Tensile test, microstructure test, microhardness test, and fatigue test were performed to investigate the effect of the copper addition on the mechanical properties of pure aluminum. The results depicted that copper addition significantly refined the aluminum grain size, which resulted in improved strength and microhardness, i.e., the fatigue strength was enhanced by more than 110% at 107 cycle, and the microhardness was enhanced by 57.9%.

Keywords: *Aluminum, Copper, Fatigue Strength, Microhardness, Microstructure*.

1. Introduction

Aluminum and its alloys are widely used in engineering applications, such as automotive and aerospace industries, because of their high strength to weight ratio, besides other desirable properties such as machinability, high thermal and electrical conductivities, high corrosion resistance, improved damping capacity and ease of use. Similar to other structures and machine components, aluminum components are usually subjected to both static and dynamic loads. One example of dynamic loads is cyclic loads which cause fatigue failures. Fatigue properties of metals and alloys have been the subject of engineering efforts for more than 150 years because fatigue is the major cause of failure in metals, i.e., fatigue is estimated to cause approximately 80% of all material failures. Thus, the economic costs of fracture due to fatigue and its prevention are quite large. For example, the annual cost of the fatigue of materials to the U.S. economy is about 3% of the gross natural product [1]. It is well-known that pure aluminum is too soft for most structural applications; therefore, the enhancement of its mechanical properties is an important requirement for engineers and metallurgists. The strengthening mechanisms of aluminum and its alloys can be introduced by strain hardening, solid solution, precipitation hardening and grain size reduction. In general, all strengthening techniques are based on the principal of restricting dislocation motion [2]. The grain refinement mechanism will be adopted in the present study for aluminum strengthening. Aluminum grain refinement can be mainly achieved by heat treatment and alloying Aluminum with other elements such as copper, titanium, boron, magnesium, etc. [3]. On the other hand, some alloying processes and heat treatments would have a great influence in making discontinuities and weak links within the material, which act as nucleation sites for pit and crack origins [4, 5]. Grain refinement does not only strengthen aluminum and aluminum alloys under static loads, but also under cyclic loads. It is recognized that materials with fine grains have a greater resistance to fatigue-crack initiation [6-8]. In addition to grain refinement mechanism, the fatigue resistance is improved by surface treatment. The surface treatment includes creating residual compressive stresses by different methods such as shot peening [9-11] and roller burnishing [12, 13]. Alloying aluminum with copper affects the strength and hardness of both heat treated and unheat treated aluminum casting alloys at both ambient and elevated service temperature [14]. It also improves the machinability of alloys by increasing the matrix hardness. The addition of copper to Al–Si alloys can form CuAl2 phases and other intermetallic compounds which increase the strength of the casting parts [15-17]. Copper also increases the heat treatability of the alloy. The addition of copper significantly decreases the melting point and the eutectic temperature of the alloy. Therefore,

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the copper increases the solidification range of the alloy [18, 19]. A previous work, by Al-Rawajfh and Al-Qawabah, studied different percentages of copper additions, namely 3, 6, and 9% Cu. They reported that the copper precipitated inside the grain as the copper percentage increased from 3 to 6, as shown in Figure 1 [20]. Therefore, it is worth to investigate the 4% Cu addition on the mechanical properties and fatigue life of pure aluminum, which is the main objective of the present study.

2. Materials, equipment and experimental procedures

2.1. Materials

Different materials have been used in the present work, namely commercially pure Al (99.8%), high purity Cu, pure graphite crucible and pure graphite rods. Copper is used as an alloying element in the present work. It was available as a powder of 99.8% purity, with a melting point of 1083^{o}C, and density of 8.2 g/cm^3 at 20^{o}C [8]. The chemical compositions, in weight percent, of aluminum are shown in Table 1.

2.2. Equipment

The following machines and equipment were used throughout the experimental work:

1. An electric resistance furnace (Type Carbolite) with 0-1100°C.
2. Digital microhardness tester (Model HWDM-3).
3. Universal Testing Machine (Qusar) with 100 KN capacities.
4. CNC lathe machine (CNC-1000L COLCHESTER).
5. Rotating Fatigue machine (HSM .19 mk.2).

2.3. Experimental Procedure

2.3.1. Preparation of Al-4%Cu alloy

The Al-4%Cu was prepared by melting the pre-calculated amount of high purity aluminum rods at 750°C, then the pre-calculated amounts of pure Cu was added to the melt in a graphite crucible. The melt was stirred for 2 minutes then poured to solidify in a brass mold and to cool in air. The Al-4%Cu alloy was synthesized in the form of 14 mm diameter and 70 mm length cylindrical rods from which test samples were machined.

2.3.2. Metallurgical Examination

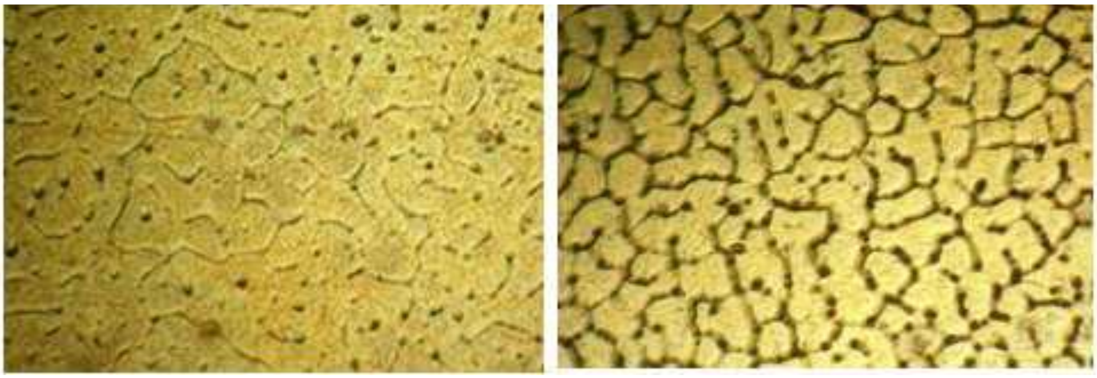
In this test, the general microstructures of pure Al and Al-4%Cu in the as cast condition were determined after grinding, polishing and etching in order to get clear microstructures. The etchant made of 1.5% HCl acid, 2.5% HNO_3, 0.5% HF acid and 95.5% H_2O by weight. Photomicrographs were obtained using the NIKON 108 type microscope at magnification of 200x.

2.3.3. Microhardness Tests

Microhardness measurements were taken on the surface of the polished Al and Al-4%Cu specimens at magnification 200x using HWDM-3 at 300 gm load. The measurements were taken for three specimens of each material and five times for each specimen. Then, the average microhardness was calculated.

2.3.4. Compression Tests

The compression test was performed to insure the homogeneity of the casted alloy when it was compared to tensile test results. Cylindrical specimens of 10 mm diameter and 10 mm length were machined using CNC lathe machine at the same cutting conditions (depth of cut, spindle speed, and feed rate). The compression test was carried out at room temperature using (Quasar 100 Universal Testing Machine of 100 KN capacity) at 10^{-3} s^{-1} strain rate. The load-deflection curve was obtained for each specimen of Al and Al-4%Cu alloy, from which the true stress-true strain curve was determined. The compression test was repeated three times for each condition, and then the average load-deflection curve was obtained.



a) Al-3wt%Cu b) Al-6wt.%Cu

Figure 1. Photomicrograph of Al-3wt.%Cu and Al-6wt.% Cu, [20]

Table 1. Chemical composition of commercially pure aluminum

Element	Fe	Si	Cu	Mg	Ti	V	Zn	Mn	Na	Al
Weight %	0.09	0.05	0.005	0.004	0.004	0.008	0.005	0.001	0.005	Rem.

2.3.5. Tensile Tests

The tensile test is probably the most important fundamental test which can be performed on material. Tensile tests are simple, relatively inexpensive, and fully standardized. The tests were carried out on work pieces at strain rate of 10^{-3} s^{-1} using Instron machine type Quasar of 100 kN capacities, the load – deflection curves were obtained from which the true stress – strain diagrams were obtained. The dimension of tensile specimen is shown in Figure 2. The tensile test was repeated three times for each material, and then the average of load-deflection has been calculated.

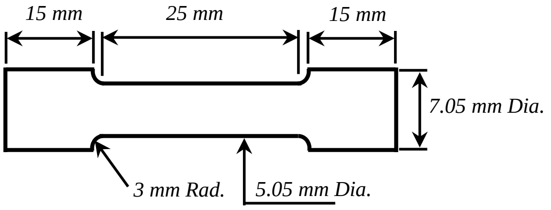


Figure 2. Tensile test specimen (ASTM-E8, 1975).

2.3.6. Fatigue Test

Rotating bending fatigue tests were performed according to ISO1143: 2010 [21]. The specimen has a circular cross section and is subjected to dead-weight loading at the free end while swivel bearings permit rotation. Points in the test-section surface, during each rotation, are subjected to sinusoidal stress variation from tension on the top to compression on the bottom. Standard fatigue specimens of the dimensions shown in Figure 3 were machined from the casted Al and Al-4%Cu ingots using a Colchester CNC-1000L lathe. Then, the specimens were mechanically polished using the same fine grades emery papers to achieve almost the same surface quality to avoid the effect of the surface conditions on fatigue results. Fatigue tests were conducted on the rotary bending fatigue machine (HSM. 19 mk. 2 apparatus) at different stress levels, where the number of cycles to fail at each stress level, was determined. The specimens rotated at 5700 rpm in a laboratory air at ambient temperature and the load ratio (i.e., σ_{min} /σ_{max}) was -1. The tests were conducted for three specimens at each stress level, and then the average life of these specimens was reported.

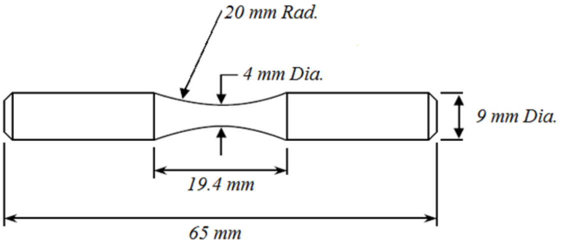


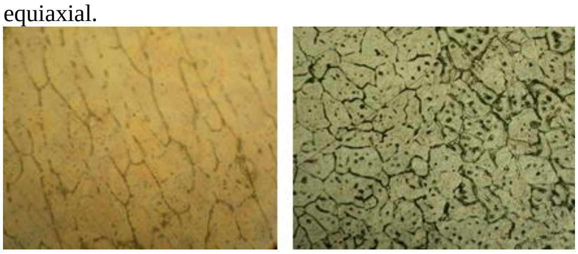
Figure 3. Standard fatigue specimen

3. Results and Discussions

3.1. Effect of Copper Addition on the Microstructure of Pure Aluminum

The microstructure of Al-4%Cu alloy at 200x magnification is shown in the Figure 4. It can be seen that the grain refinement, due to copper addition, was achieved.

The grain size decreased significantly from 124 µm for commercially pure aluminum to 30.7 µm for Al-4%Cu alloy. This reduction is attributed to the intermetallic compound that resulted after the copper addition. Moreover, the grain shape was changed from columnar to equiaxial.



a) Pure Al b) Al-4%Cu

Figure 4. Photomicroscan of (a) pure Al, and (b) Al-4%Cu at 200x magnification

3.2. Effect of Copper Addition on the Mechanical Characteristics of Pure Aluminum

Figure 5 shows the effect of 4% wt. copper addition to Al on its mechanical behavior, which is represented by true stress-true strain curve. The figure shows a very pronounced improvement in its mechanical behavior; for example, an increase of 95% in its flow stress at 20% strain. Regarding the engineering hardening index, *n*, it was 0.31 for Al and increased to 0.39 for Al-4%Cu, and the strength coefficient, *k*, was 112.17 MPa for Al and increased to 249.64 MPa after 4% wt. Cu addition. This enhancement can be attributed to the formulation of Al_2Cu intermetallic compound that restricts the grain growth during solidification, which resulted in this refinement; however, this result is consistent with the Hall pitch equation:

$$\sigma_Y = \sigma_\circ + k/d^{-1/2} \quad (1)$$

where σ_Y is the yield stress, $\sigma_\circ$ and k are constants for a particular material and d is the average grain diameter of material.

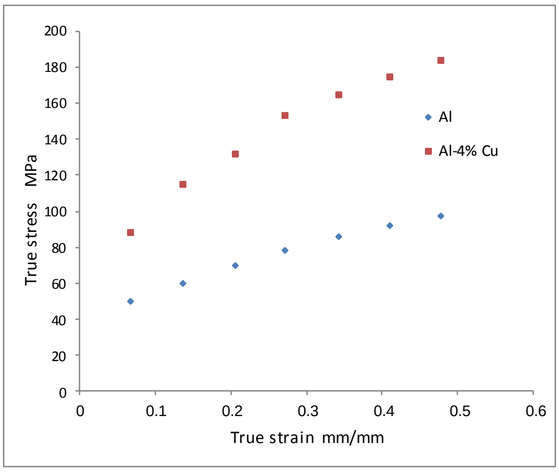


Figure 5. True stress-True strain of Al and Al-4% Cu alloy

3.3. Effect of Copper Addition on the Microhardness of Pure Aluminum Alloy by 4% Copper

It can be seen from the histogram of Figure 6 that the hardness was enhanced by 57.89% after 4% copper addition; this can be explained by the reduction of the grain size and due to intermetallic compounds formation throughout the solidification process.

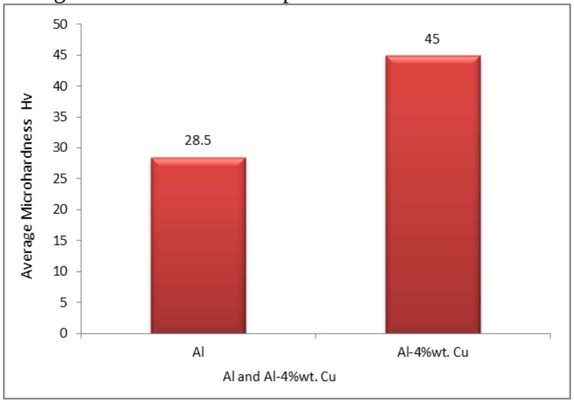


Figure 6. Average microhardness of pure aluminum and Al-4%wt. Cu alloy

3.4. Effect of Copper Addition on the Fatigue Life of Pure Aluminum Alloy by 4% Copper

Figure 7 represents the S-N diagram for Al and Al-4%Cu alloy. As shown, the addition of copper by 4% wt. significantly increases the fatigue strength (i.e., the alloying increases the fatigue strength by more than 100% that attained at 10^7 cycles). This is attributed to the effect of grain refinement resulting after the copper addition caused by intermetallic compound formed during the solidification process. The small grain size enhances fatigue strength by slowing down the crack initiation, i.e., the fine grains act as obstacles for dislocation movement which reduces the possibility of micro cracks formation. Moreover, grain refinement tends to reduce both the amount of porosity and the size of the pores in casting alloys [3]. It is well-known that the defects, like porosities in casted aluminum, have a significant effect in shortening the fatigue life by reducing the crack initiation and propagation periods [22]. Thus, reducing the amount of porosity plays a significant role in increasing the fatigue life.

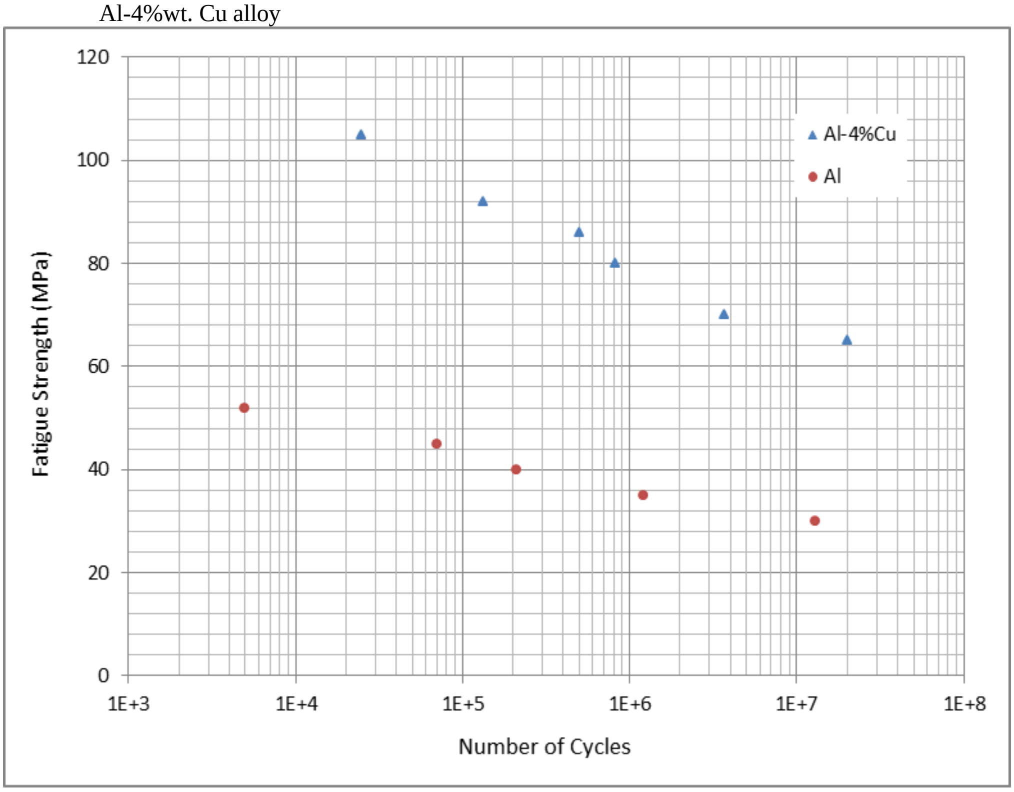


Figure 7. S-N diagram for Al and Al-4%Cu samples

4. Conclusions

The effect of alloying the aluminum by copper on some mechanical properties was investigated. In particular, copper was added at a rate of 4%wt to commercially pure aluminum. It is found that the alloying of aluminum with 4%wt of copper decreased the grain size (i.e., the copper worked as a grain refiner). Also, the alloying transforms the columnar structure to an equi-axial one.

The experiment showed that the addition of copper resulted in the enhancement of the alloy microhardness by 57.9%, and enhanced the mechanical behavior by 95% increase in its flow stress at 20% strain. Furthermore, the addition of copper by 4%wt increased the fatigue life significantly at all values of stress and shifted the S-N curve up (i.e., the alloying increases the fatigue life by 112% at 10 million cycles).

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