EFFECT OF AGING ON THE MICROSTRUCTURES AND MECHANICAL PROPERTIES OF C102 COPPER ALLOY

J. Ridhwan[1*], M. Syafiq[2], R. Hasan[3], Z. M. Zulfattah[4]

[1,2,3,4] Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka,
76100 UTeM, Durian Tunggal, Melaka, Malaysia

ABSTRACT

Aging of copper alloy was studied at different temperature and times. Tensile test and metallurgical investigation were carried out to study the effect on mechanical properties and the microstructures of copper alloy. It was observed that peak strength was obtained by specimen aged for 4 hours at 450 °C, with yield strength of 542.38 MPa and ultimate tensile strength of 559.69 MPa. Peak strength was achieved with an increased strain field in the structure produced by coherent precipitates. The finer grain structure was observed in this stage which led to strain hardening. Lowest strength was recorded on specimen aged for 8 hours at 450 °C, with yield strength of 441.66 MPa and ultimate tensile strength of 452.24 MPa. The reduction of strength was the effect of overaging, which was due to coarsening of grain structure and elimination of precipitation coherency.

***KEYWORDS**: Copper alloy, Aging, Overaging*

1.0 INTRODUCTION

Copper is an essential element for most of industrial metals because of its high ductility, malleability, thermal and electrical conductivity and resistance to corrosion. Copper and its alloys are mainly used in wiring production, piping, automotive and architecture. Heat treatment process was applied on copper and copper alloys in order to attain the desired properties for each application (Trophe, 2003).

Age-hardening is a process to enhance the strength and hardness of some metal alloys by the formation of extremely small uniformly dispersed second phase particles within the original phase matrix. However, this must be accomplished by phase transformations that are induced by appropriate heat treatments. The process is termed as precipitation hardening, as the small particles of the new phase are termed "precipitates". This process is also called 'age hardening', as

* Corresponding author email: ridhwan@utem.edu.my

the strength develops with time or as the alloy ages. The alloys that are hardened by this process are aluminum-copper, copper, beryllium, copper-tin, and magnesium-aluminum. Few ferrous alloys are also precipitation harder (Kakani, 2004).

2.0 RESEARCH METHODOLOGY

Two types of specimen are prepared for the experiment. 'Dog bone' type specimens are prepared to investigate the mechanical properties of the copper alloy while flat plate type specimens with 4 mm thickness are used for metallurgical analysis. ASTM E-8M (Standard Test Method for Tension Testing of Metallic Materials, 2010) is referred to fabricate the circular dog bone specimens.

The age-hardening process which is used in the study is the artificial aging which means that the aging process is done by reheating the specimen at certain temperatures and durations. Basically, the age-hardening process involves three stages which begins with solution treatment and followed by water quenching and reheating at desired temperature and duration. The sequence of the stages starts with solution treatment at 860 ^{o}C and soaking for 2 hours. The soaking time allows the specimen to completely homogenize. After completing the soaking time, the specimen is directly quenched into a water bath. The quenching process is conducted until the ambient temperature is reached.

For aging process, the specimen is reheated at four different temperatures with four different aging durations. The reheating temperature is set at 450 ^{o}C while the aging time is selected at 2 hours, 4 hours, 6 hours and 8 hours. Both reheating temperatures and aging time are chosen in order to obtain the desired peak value of tensile strength for the specimen. Otherwise, a longer aging time will result an over aging that can reduce the tensile strength of the specimen.

ASTM E-8 is referred to run the tensile test for heat treated specimens. INSTRON Universal Testing Machine is used to conduct the tensile test. The extension rate set for the machine is 5.00 mm/min. Yield strength and ultimate tensile strength are recorded for each specimen.

For metallurgical purpose, the specimens are undergone certain process before the microstructure can be observed under an optical microscope. The specimens are mounted in resin and followed by grinding and polishing to obtain a mirror surface. The specimens are then etched using a Marble mixture solution prior to observation under the optical microscope. The grain size and the microstructure of the specimens are studied by referring to ASTM E-112-10.

2.1 Grain Size Measurement

Grain size measurement is significant to the study since the analysis increases the relevancy and acceptability of the obtained results. Basically, the measurement involves the calculation of grain number per area. Lineal Intercept Method has been used to conduct the analysis. By referring to ASTM E112, the Lineal Intercept Method is applied to the selected area of the microstructures of treated specimens. Grain size is measured under a light microscope by determining the number of grain boundaries that intersect with a given length of a selected test area.

Based on ASTM E112, the Linear Intercept Method usesan equation as a reference for the calculation. The equation that has been used for the method is:

$$NL = Ni / (L/M) \tag{1}$$

where

NL	=	Mean number of interceptions per unit length
Ni	=	Number of intercepts or intersections counted on the field
L	=	Total test line length
M	=	Magnification

Equation 1 is used to determine the mean number of interceptions per unit length on the selected test area of the microstructures. The value which is obtained from the equation is used as a reference to find the grain size number.

3.0 RESULTS AND DISCUSSION

3.1 Tensile Properties

The tensile test recorded the yield strength and ultimate tensile strength for all specimens as shown in Figure 1 and Figure 2. In terms of yield strength, the result shows the increment of strength in the early stage of aging which is from 2 hours to 4 hours duration for both soaking temperatures. The peak yield strength is obtained on the specimen that undergone aging treatment for 4 hours. The peak value 493.88 MPa of yield strength is recorded for soaking temperature at 400 °C, and 542.38 MPa of yield strength is recorded for soaking temperature at 450 °C. Beyond the peak strength value, the specimens that undergone reheating process for 6 hours of aging and 8 hours of aging show gradual decrement in yield strength.

For ultimate tensile strength, the pattern of the result is similar to that of yield strength result. The ultimate tensile strength is increasing in the early stage of aging duration and reaches the peak value of ultimate tensile strength at 4 hours of aging duration for both soaking temperatures. The peak value of ultimate tensile strength is obtained at 400 °C soaking temperature, which is 509.76 MPa, while 559.69 MPa of ultimate tensile strength is obtained at 450 °C soaking temperature.

Table 1. Tensile properties of heat treated copper alloy based on the effect of aging treatment

Aging Duration (h)	$T_1 = 400°C$		$T_2 = 450°C$	
	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
2	421.25	434.15	510.01	526.41
4	493.88	509.76	542.38	559.69
6	476.95	487.32	482.02	503.32
8	452.10	464.90	441.66	454.24

Based on Table 1, two graphs are plotted. One graph is plotted for yield strength result while the other is plotted for ultimate tensile strength result.

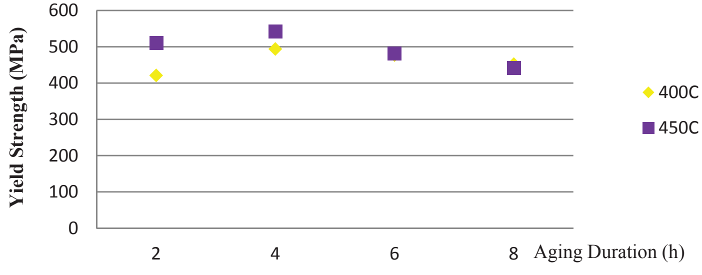

Figure 1. Effect of aging process on yield strength

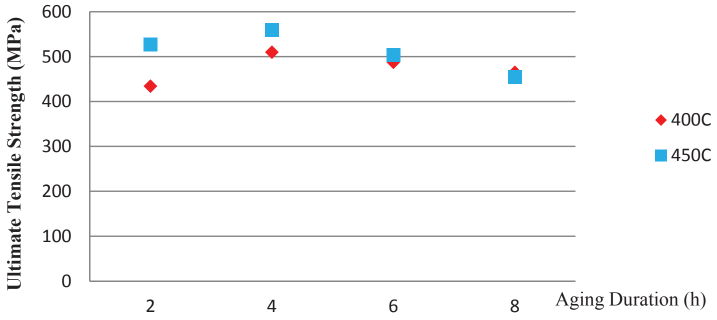

Figure 2. Effect of aging process on ultimate tensile strength

The aged specimens have undergone prior processes before aging which are solution heat treatment at 860 °C and 2 hours soaking. Then, it was followed by water quenching. The specimens are then reheated at certain aging durations which are 2 hours, 4 hours, 6 hours and 8 hours. Based on the result, it can be seen that the ultimate tensile strength properties and yield strength properties are gradually increased to the peak and begin to decrease beyond the peak value, which are due to certain factors as will be explained shortly.

After quenching process, precipitation is formed by reheating process at selected temperatures. At this stage, the precipitate was nucleated at localized region. Since the precipitate is having a higher solute content, the region surrounded by the matrix was reduced in solute content. A concentration gradient was formed due to the diffusion of solute atoms from adjacent matrix toward the particles and the precipitates were allowed to continuously grown (Nunez, 2001).

At the early stage of the aging process, the increment of strength is due to the clustering grain region that formed in the microstructure as a result of water quenching. The clustered grain produces local strain that leads to the increment of yield strength and ultimate tensile strength. On the peak strength, the formation of coherent precipitate produces an increased strain field in the microstructure. An ordered, metastable and coherent alloy phase was found to be mainly responsible for maximum strengthening as present in the peak condition (Nagarjuna, 2001).

The decreasing of yield strength and ultimate tensile strength beyond the peak value is mainly caused by the overaging. The overaging mechanisms which take place beyond the peak strength contribute to the grain growth. Loss of coherency of precipitate is the main factor that induces to the grain growth. As a result, the loss of coherency contributes to the softening of specimen and gradual decrease in yield strength and ultimate tensile strength of aged copper alloy (Dieter, 2012).

3.2 Microstructure observation

The optical microscope images show the microstructures of annealed specimens and water quenched specimens as shown on Figure 3 and Figure 4.

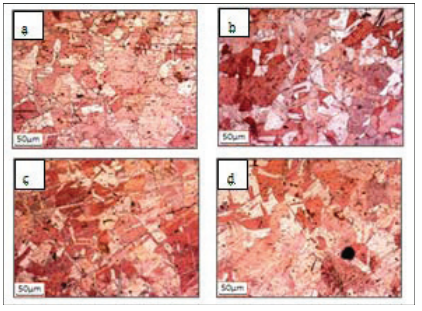

Figure 3. Microstructure of aged copper alloy at T = 400 ^{o}C,
a) 2 h b) 4 h c) 6 h d) 8 h

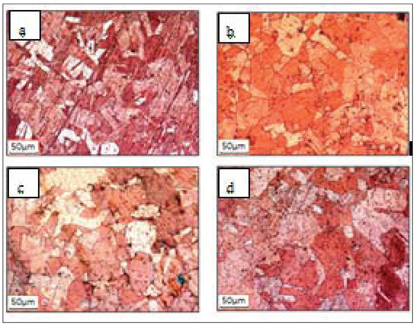

Figure 4. Microstructure of aged copper alloy at T = 450^{o}C,
a) 2 h b) 4 h c) 6 h d) 8 h

The grain size is becoming smaller during the early stage of aging duration until reaching the peak value at 4 hours of duration. Once the aging process has undergone beyond the peak value, the grain growth is observed until the aging duration of 8 hours. At this stage, a coarser grain structure is showed especially in the microstructure of aged copper alloy at 450 ^{o}C for 8 hours duration.

The precipitates are formed in the aging specimens due to the re-heatreatment after the solution treatment and quenching process. In the precipitation process, the saturated solid solution first develops solute cluster, which then involves in the formation of transitional precipitates (Nunes, 2001). The precipitates play a main role in the changes of microstructure in aging specimen. The mechanism of strengthening from precipitation involves the formation of coherent of solute atoms. This causes a significant effect to the microstructure which leads to the clustering of the grain, and this fact can be proven from the aging specimen result with 4 hours duration. The overaging mechanisms contribute to the grain growth due to the loss of coherency of precipitate.

3.3 Grain size measurement

By using the Linear Intercept Method on ASTM E-112-10, the grain size numbers of the specimens are obtained. Table 2 below shows the grain size number that has been calculated for the specimens at different cooling rates. Meanwhile, Figure 5 shows the graph plotted from the data obtained in Table 2.

Table 2. Grain size number of copper alloy based on the effect of aging duration (Higher number represent greater grain size)

Aging Duration (h)	Grain size number, G	
	$T_1 = 400^oC$	$T_2 = 450^oC$
2	9.4	9.7
4	12.1	12.9
6	10.5	11.2
8	7.3	6.3

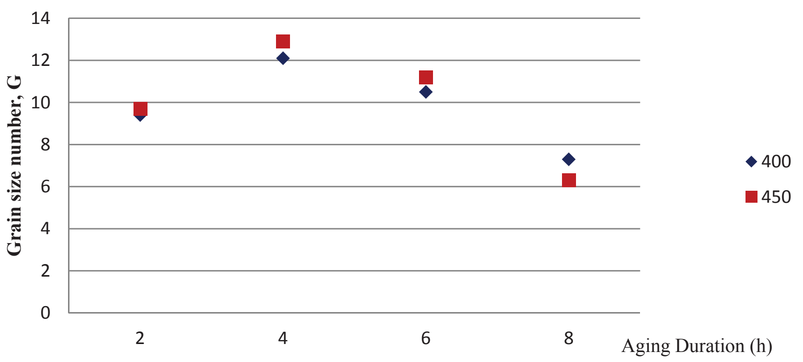

Figure 5. Effect of aging on grain size number
(Higher number represent greater grain size)

The grain number is gradually increased until 4 hours of aging duration and begins to decrease beyond 4 hours of aging duration for both aging temperature. The changes in the grain size number for each aging specimens depend on the grain size of the specimen after undergone different aging durations. At the early stage of aging duration which is between 2 hours to 4 hours, the grain size number is increased due to the effect of water quenching after solution treatment. The local stress within the grain induces the grain clustering. A higher number of grain boundaries can be observed in the specimen, thus more interception can be done. The clustering of grains contributes to the increment of the grain size number. The highest recorded grain size number is 12.9 for the specimen treated at 450 ^{o}C for 4 hours aging duration. Beyond 4 hours of aging duration, the specimen has undergone grain growth due to the overaging. Thus, the number of interceptions that can be done was less and smaller mean number of interceptions per unit length is obtained.

Based on the Hall-Petch theory, a higher grain size number shows that the clustering grain structure is based on the barrier effect of grain boundaries to slip propagating from grain to grain and from the buildup of stress concentration due to the increment of dislocation density. As the grain size is reduced, the degree of grain constraint is increased. The grain boundaries thickness and area will be reduced and forced the grain to cluster to each other. The higher stress also indicates that greater energy is required to produce the clustering region. This leads to the increase in the strength of the structure (Adnyana, 2005).

4.0 CONCLUSION

The copper alloy reaches the peak strength at the 4 hours of aging duration due the coherent precipitation. The peak yield strength obtained for aging copper alloy is 493.88 MPa at 400 ^{o}C and 542.38 MPa at 450 ^{o}C, while the peak tensile strength recorded for both 400 ^{o}C and 450 ^{o}C of soaking temperatures are 509.76 MPa and 559.69 MPa respectively. The tensile strength values of aging treated copper alloy are slightly improved until the peak value, and the reduction of tensile strength occurrs beyond that peak value. A finer grain structure is observed in the early stage of aging which is between 2 hours to 4 hours of aging duration. The highest grain size number is recorded for the peak strength at 4 hours duration which is 12.9. Beyond that duration, a coarser grain structure is observed. In terms of grain size measurement, the aging specimen with the peak strength shows the highest grain size number compared to the annealing specimens and quenching specimens.

5.0 ACKNOWLEDGEMENT

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