INFLUENCE OF HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ALUMINUM BRONZE

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ABSTRACT

The present investigation deals with the study relating the response of aluminum bronze (Cu-Al-Fe alloy) under the condition of changing heat treatment parameters and type. The types of heat treatment employed in this investigation were solutionizing and ageing. The solution treatment was carried out at two temperatures (850°C and 900°C) and duration in the range of 0.5, 1, 1.5 and 2 hrs respectively. Similarly, ageing was carried out at 300°C, 400°C and 500°C wherein the duration of the ageing was maintained at 2 and 3 hrs respectively. The heat treated samples were subjected to water quenching in order to bring them to ambient temperature. The behavior of the alloy has been assessed in terms of the influence of the type, temperature and duration of the heat treatment on the microstructural and mechanical properties of the samples. Results showed that as cast alloy showed granular structure consisting of primary α, eutectoid α+γ₂ and Fe rich phase. Solutionizing led to the microstructural homogenization by way of the elimination of the dendrite structure and dissolution of the eutectoid phase and other microconstituents to the form the single phase structure consisting of β. This was followed by the formation of the β’ martensite, retained β and α. Ageing brought about the transformation of the martensite and other microconstituents into the eutectoid phase. Also, solutionizing at 850°C for 2 hrs led the alloy to attain the highest hardness in the category of solutionized samples while ageing at 300°C for 2 hrs offered maximum hardness amongst the aged samples. The as cast alloy attained highest compressive strength and strain followed by that of the heat treated samples while the trend reversed as far as their tensile properties are concerned.

KEYWORDS: Aluminum Bronze, Heat Treatment, Microstructure, Mechanical Properties, Microstructure Property- Correlations

INTRODUCTION

The aluminum bronzes are a range of copper based alloys in which aluminum up to 14% is the primary alloying element. They are available in both cast and wrought form [1]. Major alloying elements other than Al include iron, nickel, manganese, tin or silicon to improve mechanical properties and alter microstructure [1]. Aluminum bronzes are classified into two kinds, the binary aluminum bronze and the multi-component aluminum bronze [2]. By varying the concentration of alloying elements, a family of commercial aluminum bronze with high strength and excellent corrosion resistance is readily available for practical application at temperatures up to 400°C [5].

It is well known that aluminum bronze has excellent physical, mechanical and tribological properties, and is a material commonly used for some mechanical parts with wear- and abrasion-resistance [4]. These excellent properties, favorably comparing with low-alloy steels and cast irons, make aluminum bronzes one of the most versatile engineering materials [5]. Al-bronzes with approximately 8% Al is suitable for cold forming, and the duplex alloys with 10% Al are suitable for casting process [3]. The mechanical properties of these aluminum bronzes depending on their chemical
compositions can be improved significantly with heat treatments [3]. Bronze alloyed with about 10% Al (in weight) exhibits the best comprehensive properties among the most widely used materials in the aluminum bronze family [4].

Al bronzes containing Al above 8.4% respond to heat treatment in a manner similar to steels. Heat-treating processes include solution treating and ageing are very popular and useful for property improvement and has been applied to many Al bronzes in practice. An appraisal of the above suggests that heat treatment plays an important role in controlling the end properties and resulting microstructural features of Al bronzes.

In view of the above, an attempt has been made in this investigation to optimize the solutionizing and ageing parameters like the duration and temperature of the treatments and characterize their microstructural features and mechanical properties with an objective to establish microstructure-property correlations and develop desired combinations of microstructural features and properties.

**EXPERIMENTAL PROCEDURE**

The methodology adopted to carry out the present study essentially involved alloy preparation by melting and casting technique, its heat treatment (solutionizing and ageing) over a range of temperatures and durations, optimization of heat treatment parameters (temperature and duration), sample preparation from the alloy in as cast and heat treated conditions, characterization of microstructural features and mechanical properties.

**Alloy Preparation**

The Al bronze with a nominal composition of Cu-10Al-3Fe was synthesized using liquid metallurgy route. The process started with the preparation of the charge containing required quantities of different elements like Cu, Al, and Fe. Cu pieces were charged in a graphite crucible and melted employing an oil-fired furnace. The melt surface was covered with flux (Albral) and other alloying elements were added to the melt (maintained at 1170°C) gradually. Care was taken to add the lower melting elements like Al to add at latter stages of melting with a view to reduce losses through vaporization. The melt was stirred manually for some time to facilitate dissolution of the alloying elements. After cleaning the melt surface, pouring was carried out in permanent moulds in the form of 14 mm diameter, 150 mm long cylindrical rods.

**Heat Treatment**

The type of heat treatments employed in this investigation consisted of solutionizing and artificial ageing. Solutionizing was carried out at 850°C and 900°C for 0.5, 1, 1.5 and 2 hrs respectively, while ageing was done at 300°C, 400°C and 500°C for 2 and 3 hrs respectively. The samples were solutionized at 850°C and 900°C prior to subjecting them to ageing. Water quenching was employed to bring the heat treated samples to ambient temperature after the solutionizing and ageing treatments.

**Microstructural Studies**

Microstructural examination was carried out on metallographically polished samples using optical microscopes of Leica make computerized optical microscope attached with a digital photographic and data storage and retrieval system. The methodology adopted for samples preparation for the purpose involved polishing of samples using different grades of emery papers such as 120, 320, 400, 600, 800 & 1200 grits, 1/0, 2/0, 3/0, 4/0 grades in descending order. Care was taken to continue polishing on a specific grade of emery paper until the scratches/polishing marks created by the previous paper were totally removed. Also, the direction of polishing on a typical polishing paper was kept normal to that of the previous one. Polishing on emery papers was followed by cloth polishing using alumina suspension. In this case, the device used was a polisher equipped with a rotating wheel. The wheel was covered with a polishing cloth and it rotated at a controlled
speed with the help of an electric motor and regulator assembly. The samples were rinsed well with water and acetone in order to clean the specimen surface. The samples were then etched using potassium dichromate solution.

**Hardness Test**

Hardness of the samples was measured using a Vickers hardness tester at an applied load of 30 kg. The samples were polished metallographically prior to their hardness measurement. An average of 5 observations has been considered in this study.

**Tensile and Compression Tests**

Tensile tests were performed on round specimens having 4 mm gauge diameter and 20 mm gauge length at a strain rate of $4 \times 10^{-3}$ s$^{-1}$. An average of two observations has been considered in this study. Cylindrical specimens (size: 10 mm diameter and 15 mm long) were used for conducting compression tests at a strain rate of $10^{-3}$ s$^{-1}$. The equipment used for carrying out the tensile and compression tests was an Instron make universal testing machine.

**RESULTS**

This study deals with the observations made pertaining to the characteristics of the samples as influenced by the type of heat treatment (solutionizing and ageing) parameters (duration and temperature). Response of the samples was assessed in terms of their microstructural features and mechanical (hardness and tensile and compressive strength and ductility) properties.

**Microstructure**

Fig. 1 shows microstructural characteristics of the as cast Al bronze. It shows granular structure (Fig.1a). Different microconstituents like primary $\alpha$, eutectoid $\alpha+\gamma_2$ along with Fe-rich phase are shown in Fig. 1b (regions marked by A, B and arrow respectively).

Figure 2 shows microstructure of the samples solutionized at 850$^\circ$C. Solutionizing at this temperature for 0.5 hr led to the breaking of the as cast structure and dissolution of the eutectoid and primary precipitates in the matrix (Fig. 2a). Improved microstructural homogeneity in this case (Fig. 2) over the as cast one (Fig. 1) may also be noted. Increasing solutionizing duration led to a higher extent of dissolution and grain/precipitate coarsening that ultimately resulted into coarser $\beta^\prime$ (Fig. 2 b versus a).

The microstructural features of the samples solution treated at 900$^\circ$C are shown in (Fig. 3). Coarsening of the microconstituents and higher extent of dissolution of the as cast microconstituents at the higher solutionizing temperature (900$^\circ$C) compared to that at 850$^\circ$C was observed in general (Fig. 3 versus 2).

Microstructures of the samples aged at 300$^\circ$C and 500$^\circ$C are shown in (Fig. 4 and 5 respectively). Ageing at 300$^\circ$C for 2 hrs caused the precipitation of the $\gamma_2$ phase in a uniform manner along with some (undissolved) grain boundary precipitates (Fig. 4a). Increasing ageing duration enhanced the process of forming and limited coarsening of the eutectoid $\alpha+\gamma_2$ (Fig. 4 b versus a) phase as well more effective dissolution of the grain boundary precipitates (Fig 4 b versus a).

Increasing the ageing temperature to 500$^\circ$C caused more effective formation of the eutectoid phase along with better defined lamellae of the $\gamma_2$ phase compared to that at 300$^\circ$C (Fig. 5a versus 4a) while increasing the ageing duration at 500$^\circ$C from 2 to 3 hrs led to the complete dissolution of the grain boundary precipitate and completion of the eutectoid transformation with improved lamellarity of $\gamma_2$ (Fig. 5b versus a).
Figure 1: Microstructural Features of the as Cast Aluminum Bronze Samples Showing Dendrite Structure and Different Microconstituents (a): Primary $\alpha$, (b): Eutectoid $\alpha+\gamma_2$, Single Arrow: Fe

Figure 2: Microstructural Features of the Aluminum Bronze Samples Solution Treated at 850°C for (a) 0.5 hr and (b) 2 hrs

Figure 3: Microstructural Features of the Aluminum Bronze Samples Solution Treated at 900°C for (a) 0.5 hr and (b) 2 hrs

Figure 4: Microstructural Features of the Aluminum Bronze Samples Solution Treated at 850°C for 2 hrs Followed by Ageing at 300°C for (a) 2 hrs and (b) 3 hrs
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Figure 5: Microstructural Features of the Aluminum Bronze Samples Solution Treated at 850°C for 2 hrs Followed by Ageing at 500°C for (a) 2 hrs and (b) 3 hrs

Mechanical Properties

Figure 6 shows the hardness of the samples plotted as a function of the duration of heat treatment. The influence of the temperature of heat treatment (solutionizing and ageing) on the hardness property is also evident from the figure. The data point corresponding to zero duration on the hardness axis corresponding to the solutionized samples refers to the property of the as cast sample while the one corresponding to the aged samples represents the hardness of the alloy solutionized at 850°C for 2 hrs. This has been done with a view to truly assess the influence of solutionizing and ageing treatments by comparing their property with the one representing their just previous conditions. The heat treated (solutionized and aged) samples attained significantly higher hardness than that of their as cast counterpart. The hardness of the solutionized samples tended to decrease initially, attain the minimum, increase thereafter followed by a reduction in the property with the increasing solutionizing duration at the higher temperature (900°C). The trend observed at the lower temperature (850°C) was identical to that at 900°C except that no deterioration in hardness was observed towards the end of the treatment. Solutionizing temperature showed a mixed influence on hardness wherein the hardness was higher at the higher temperature in the intermediate duration of solutionizing while the trend reversed at remaining durations. Aged samples attained the highest hardness amongst all (as cast, solution treated and aged). Further, the hardness either remained practically unaffected or tended to decrease with increasing ageing duration. Increasing ageing temperature up to 400°C led to decreased hardness while a further rise in temperature to 500°C delineated hardness to lie in between 300°C and 400°C.

Figure 6: Hardness of the Aluminum Bronze Samples Plotted as a Function of the Duration of Solutionizing and Ageing Treatments. The Effect of the Temperature of Solutionizing (850°C and 900°C) and that of Ageing (300°C, 400°C and 500°C) on the Hardness Property is also Shown in the Figure
Tensile stress versus strain plots for the samples are shown in Fig. 7. The stress increased with strain. The rate of increase in stress was high initially. This was followed by a lower rate of increase in stress with strain, attainment of maximum stress and specimen fracture. Figure 8 shows mechanical properties of the samples in as cast and optimized heat treated (solutionized and aged) conditions. The heat treated alloy attained superior strength and elongation compared to it’s as cast version (Fig. 7 & 8). A comparison of the characteristics of the solutionized and aged alloy samples suggests that the aged samples delineated higher hardness and tensile strength than those of the solutionized samples while their elongation tended to follow a reverse trend (Fig. 7 & 8).

The compressive stress-strain plots of the aluminum bronze in as cast and heat treated conditions are presented in Fig.9. Increasing stress level with strain was recorded in all the cases prior to specimen failure wherein the rate of increase in stress was high initially. This was followed by a reduction in the rate of increase in stress and ultimately specimen fracture. The rate of decrease in stress at larger strain levels was the lowest in the case of the as cast alloy followed that of the solutionized and aged samples. Figure 10 delineates the ultimate compressive strength and strain in the case of the as cast and heat treated alloys. It may be noted that the strength of the heat treated alloy samples was somewhat inferior to that of the as cast alloy while the aged samples attained higher strength compared to that of the solutionized ones (Fig 10). As far as reduction in height is concerned, it was the maximum for the as cast alloy followed by that of the solutionized and aged samples (Fig. 10).

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**Figure 7**: Tensile Stress-Strain Plots of the Aluminum Bronze Samples in as Cast and Heat Treated Conditions

[ST: Solutionizing at 850°C for 2hrs, Aged: Ageing at 300°C for 2 hrs]

**Figure 8**: Typical Mechanical (Hardness and Tensile) Properties of the Aluminum Bronze Samples in as Cast and Heat Treated Conditions [ST: Solutionizing at 850°C for 2 hrs, Aged: Ageing at 300°C for 2 hrs]
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Figure 9: Compressive Stress-Strain Plots of the Aluminum Bronze Samples in as Cast and Heat Treated Conditions [ST: Solutionizing at 850°C for 2 hrs, Aged: Ageing at 300°C for 2 hrs]

Figure 10: Typical Mechanical (Hardness and Compression) Properties of the Aluminum Bronze Samples in as Cast and Heat Treated Conditions [ST: Solutionizing at 850°C for 2 hrs, Aged: Ageing at 300°C for 2 hrs]

An appraisal of the observations made in this study suggests that the microstructural features and mechanical properties of the bronze samples are greatly controlled by the heat treatment parameters like temperature and duration of the treatments (solutionizing and ageing). Solutionizing caused the elimination of the as cast structure and microstructural homogeneity along with the formation of mainly martensite. Increasing solutionizing duration and temperature of solution treatment brought about more effective dissolution of the as cast microconstituents initially and coarsening of the resulting microconstituents at the latter stages. Similarly, ageing brought about the formation of the eutectoid phase at the cost of the previously formed martensite. Rise in the temperature and duration of ageing led the eutectoid transformation to take place more effectively along with the formation of better defined lamellae of the (eutectoid) phase and dissolution of grain boundary precipitates. Solutionizing at 850°C for 2 hrs led the alloy to attain the highest hardness in the category of solutionized samples while ageing at 300°C for 2 hrs offered maximum hardness amongst the aged samples. Also, the tensile and compressive properties were significantly noted to alter as a result of the heat treatments. The response of the samples under tensile and compressive modes of loading was different. For example, the as cast alloy attained highest compressive strength and strain followed by that of the heat treated samples while the trend reversed as far as their tensile properties are concerned.

DISCUSSIONS

Microstructural features of the as cast Al bronzes are controlled by the solidification behavior of the alloy system and cooling conditions employed during alloy preparation. Interestingly, equilibrium phases (according to Cu-Al phase diagram) are formed at slow cooling rates like 50°C per hour (sand casting of thick sections). Accordingly, the equilibrium of as cast structure comprises of primary α phase, eutectoid α+γ2 and Fe-rich phases (Fig. 1b, regions marked...
by A, B and arrow respectively). However, cooling rates much higher than that of the equilibrium one are generally experienced in practice. This leads to the generation of martensite ($\beta'$) or bainite ($\alpha'$) depending on the rate of cooling.

Some retained $\beta$, proeutectoid $\alpha$ and/or eutectoid $\alpha+\gamma_2$ phase may also be visible in the quenched sample depending on the alloy composition and rate of cooling. The presence of Fe leads to microstructural refinement, improved thermal stability, superior mechanical properties through precipitation hardening, restricted growth of $\beta$ grains at high temperatures [6] and suppressed formation of the unwanted $\alpha+\gamma_2$ phase; the $\gamma_2$ phase is hard and brittle and produces embrittlement in the alloy system [7]. Fe-rich particles (Fig. 1b, region marked by arrow respectively) are formed in the temperature range of 350-400°C [8]. Further, it is not possible to obtain a fully martensitic structure in the alloys even at very high quenching rates [8] since Fe is enriched in the $\alpha$-phase [9,10]. This enables Fe to stabilize $\alpha$ phase and hence suppress the martensitic transformation and favour the formation of bainitic structures [8,11-13].

During solutionizing, heating to above 850°C leads to the generation of 100% $\beta$. Most of the $\beta$ phase is built up after a few minutes (Fig. 2) at the solution temperature [8]. Prolonged soaking (Fig. 3b) at this temperature leads only to minor changes in the direction of the equilibrium state [8]. The diffusion rate of Al in the $\beta$ phase is much higher than in $\alpha$ phase [8]. Accordingly, if there is any $\alpha$-phase in the structure, there will be no grain growth [14]. Only after complete dissolution of the $\alpha$-phase, does a rapid growth in grain size occur (Fig. 2) producing grain sizes in the region of a few millimetres [8]. In complex alloys containing Fe [15], the solution-treatment temperature has been found to have a significant influence (Fig. 2 versus 3). Increasing the solutionizing temperature leads to the dissolution of more particles (Fig. 3), hence higher strength and lower ductility are achieved after subsequent cooling [8]. Holding below ~850°C results in increasing amount of $\beta$ co-existing with $\alpha$ and, hence the quenched alloy has an increasing amount of soft $\alpha$ present [16].

Characteristics of Al bronzes are sensitive to their microstructural features and chemical compositions. The type and parameters employed during heat treatment also greatly control their microstructural features (Fig. 2 and 3). Higher hardness of the solutionized alloy samples than that of the as cast specimens (Fig. 6) could be attributed to structural homogenization and solid solution hardening and strengthening as also agreed by the formation of martensite or bainite (Fig. 2) as a result of quenching after solutionizing. Further, higher hardness of the aged alloy compared to that of the solutionized samples (Fig. 6) could have resulted from the precipitation of the eutectoid $\alpha+\gamma_2$ (Fig. 3) which is harder than that of the martensite or bainite formed after solutionizing (Fig. 2). It has been observed that martensite in the case of Cu-Al alloys is slightly softer than that of the corresponding eutectoid ($\alpha+\gamma_2$) phase, the latter in view of the high hardness of the $\gamma_2$ phase [16]. Moreover, a reduction in hardness at increasing ageing temperature (Fig. 6) was a result of coarsening of the eutectoid phase (Fig. 3). It has been suggested that even though the eutectoid phase is harder than that of the $\beta'$ (martensite), the large amount of primary $\alpha$ may make the alloy softer even after the formation of the eutectoid phase [16].

Properties of Cu-Al alloys containing primary $\alpha$ depend on the grain size and shape of the primary $\alpha$ phase; finer the primary $\alpha$ phase, the greater the tensile strength of the bronze [16]. Also, coarser primary $\alpha$ grains reduce the strength and ductility significantly despite identical hardness values [16]. Rapid cooling from a temperature below the eutectoid one causes the formed structure to offer minimum strength and a low ductility [17,18]. The highest strength at a low ductility in quenched alloy is caused by the formation of martensite phase (Fig. 2 & 3). Higher hardness is observed with increasing tempering temperatures from 100°C to 500°C (Fig. 6) in Cu-Al-Fe alloys due to a precipitation hardening [19]. Aluminum bronze attains excellent hardness, tensile and compressive strength at room temperature (Fig. 7-10).

From the above discussion, it emerges that the microstructural features of Al bronzes are very much sensitive to their processing steps and associated parameters like temperature, cooling rate and duration of processing/treatments.
Moreover, the response of the bronzes very much depends on the nature of various microconstituents and their volume fraction and morphology (shape and size). Accordingly, it becomes imperative to exercise due care in optimizing the processing parameters and analyzing the results.

CONCLUSIONS

This study presents conclusions arrived at based on the results obtained and observations made in this investigation. The conclusions relate to the microstructural alterations brought about by heat treatment involving solutionizing and ageing and corresponding changes in mechanical properties such as hardness, tensile and compressive properties. Following are the conclusions drawn:

a) The alloy displayed primary α, eutectoid $\alpha+\gamma_2$ as well as retained β and martensite β’. Heat treatment led to microstructural alterations significantly depending on the type and parameters employed. For example, solutionizing brought about microstructural homogenization through the disappearance of the as cast structure. The degree of (microstructural) homogeneity increased with the increasing duration and temperature of solutionizing. Coarsening of phases was also observed especially at higher temperatures and durations of the treatment. Ageing caused the formation of the eutectoid phase along with the retained/untransformed martensite and microconstituents displayed were α. Ageing at 500°C led to the transformation of martensite into the stable eutectoid structure with better defined lamellae while the lamellae were not so well defined at 300°C. Rising ageing duration led to structural coarsening.

b) Hardness of the samples improved after heat treatment compared to the one in as cast condition. During solutionizing at 90°C, the hardness decreased initially followed by the attainment of the minimum and a reversal in the trend at still longer durations ultimately tending to decrease once towards the end. A similar trend was also observed at 85°C, except that no deterioration in hardness was observed towards the end of the treatment. Solutionizing temperature showed a mixed influence on hardness. Aged samples attained the highest hardness amongst all. Also, the hardness either remained practically unaffected or tended to decrease with increasing ageing duration while increasing ageing temperature up to 40°C led to a decreased in hardness while a further rise in temperature to 50°C delineated hardness to lie in between 300 and 40°C.

c) The tensile stress increased with strain. The rate of increase in stress was high initially. This was followed by a lower rate of increase in stress with strain, attainment of maximum stress and specimen fracture. The heat treated alloy attained superior tensile strength and elongation as compared to that in the as cast condition. The aged samples attained higher hardness and tensile strength than those of the solutionized samples while their elongation tended to follow a reverse trend.

d) During compression loading, higher stress was recorded with increasing strain prior to specimen failure. In this case, the rate of increase in stress was high initially. This was followed by a reduction in the rate of increase in stress and ultimately specimen fracture. Moreover, the compressive strength of the heat treated alloy samples was somewhat inferior to that of the as cast alloy while the aged samples attained higher strength compared to that of the solutionized ones. Reduction in height was the maximum for the as cast alloy followed by that of the solutionized and aged samples.

The study suggests that the microstructural features and mechanical properties of the samples to be affected by heat treatment significantly. The type (solutionizing and ageing) and parameters (temperature and duration) of heat treatment also affected the characteristics of the sample to a considerable extent. Accordingly, it emerges from the study that it is possible to obtain desired combinations of properties through optimizing the heat treatment type and parameters.
REFERENCES


