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Original scientific paper

EFFECT OF HEAT TREATMENT PARAMETERS ON THE MECHANICAL PROPERTIES AND MICROSTRUCTURE OF ALUMINIUM BRONZE

Božidar MATIJEVIĆ, Thota Surya Krishna SUSHMA, B. K. PRATHVI

Abstract: Aluminium bronzes are used for their combination of high strength, excellent corrosion and wear resistance. This paper presents the research of heat treatment parameters of two different chemical compositions of aluminium bronze (Cu-Al-Fe- Ni alloy) on microstructure and mechanical properties. The heat treatment employed in this research were solutionizing and tempering. The solution treatment was carried out at a temperature of 950 °C and the duration in the range of two hours. Similarly, tempering was carried out at 300 °C and 400 °C, wherein the duration was maintained at two hours. The heat treated samples were subjected to the cold water quenching in order to bring them to an ambient temperature. Metallographic studies were performed on samples in order to determine the changes in the microstructure of the hardened bronze, on the metallographic microscope OLYMPUS GX51 with a digital image analysis and the scanning electron microscope TESCAN VEGA 5136MM with EDX along with the digital recording on the computer. Moreover, the Glow Discharge Spectroscopy-GDS was done to determine the chemical composition of the samples. The results of the chemical composition for the aluminium bronze AK2 were: Cu- 78,37%; Al- 10,52%; Fe- 4,44%; Ni- 5,16% and for AK3 alloy: Cu- 78,95%, Al- 10,97%; Fe- 4,16%; Ni- 4,8%. The behavior of the alloy has been assessed in terms of the influence of the temperature and duration of the heat treatment on the microstructural and mechanical properties of the samples. The hardness of samples was measured by using a Vickers hardness tester at an applied load of one kg. The samples were polished metallographically prior to their hardness measurement and an average of three observations has been considered. The hardness of the AK2 alloy increased from 320 HV1 to 425 HV1 after quenching and to 500 HV1 after tempering on 300 °C or 540 on 400 °C. The hardness of the AK3 alloy increased from 300 HV1 to 400 HV1 after quenching and to 475 HV1 after tempering on 300 °C or 470 on 400 °C.

Keywords: aluminium bronze; heat treatment; GDS; mechanical properties; microstructure

1 INTRODUCTION

Aluminium bronze is a type of bronze in which aluminium is the main alloying metal added to copper, in contrast to the standard bronze (copper and tin) or brass (copper and zinc). A variety of aluminium bronzes of differing compositions have found industrial use, with most ranging from 5% to 11% of aluminium by weight, the remaining mass being copper. Other alloying agents such as iron, nickel, manganese, and silicon are also sometimes added to aluminium bronzes [1]. Aluminium bronzes are used for their combination of high strength, excellent corrosion and wear resistance. Aluminium bronze alloys typically contain 9-12% of aluminium and up to 6% of iron and nickel. Alloys in these composition limits are hardened by a combination of a solid solution strengthening, cold work and precipitation of an iron rich phase. The vertical section through the Cu-Al-5%Ni-5%Fe phase diagram is shown in Fig. 1 [2].

High aluminium alloys are quenched and tempered. Aluminium bronzes are used in marine hardware, shafts, pump and valve components for handling sea water, sour mine waters, non-oxidizing acids and industrial process fluids. They are also used in the applications such as heavy duty sleeve bearings and machine tool ways. They are designated by UNS C60800 through C64210 [3]. Aluminium bronzes containing Al above 8.4% respond to heat treatment in a manner similar to steel. The heat-treating processes such as solution treating and tempering are useful for property improvement and have been applied to many Aluminium bronzes in practice. An appraisal of the above suggests that heat treatment plays an important role in controlling the end properties and the resulting microstructural features of Aluminium bronzes [4, 5]. In view of the above, an attempt has been made in this research to optimize the solutionizing and tempering parameters such as the duration and temperature of the treatments, and to characterize their microstructural features and mechanical properties with an objective to establish the microstructure-property correlations and develop the desired combinations of microstructural features and properties.

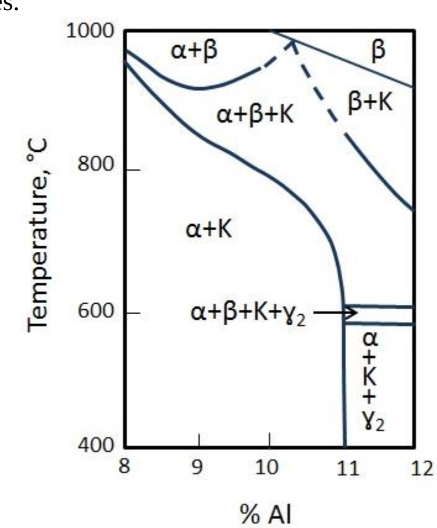
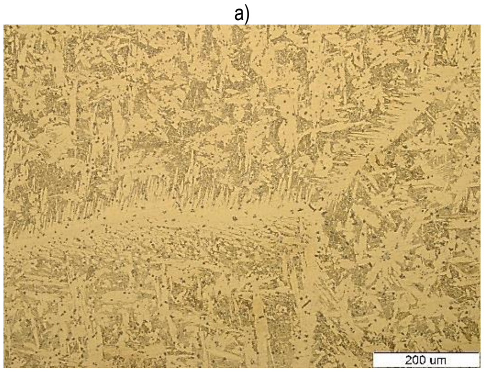


Figure 1 Vertical section through the Cu-Al-5%Ni-5%Fe phase diagram

2 EXPERIMENTAL PROCEDURE

The methodology adopted to carry out the present study essentially involved heat treatment (solutionizing and tempering) over a range of temperatures and durations, the optimization of heat treatment parameters (temperature and duration), characterization of microstructural features and mechanical properties. The type of heat treatments employed in this research consisted of solutionizing and tempering. The solution treatment was carried out at a temperature of 950 °C and the duration in the range of two hours. Similarly, tempering was carried out at 300 °C and 400 °C maintaining the duration at two hours. The heat treated samples were subjected to cold water quenching in order to bring them to an ambient temperature after solutionizing. The Glow Discharge Spectroscopy-GDS was done to determine the chemical composition of the samples. Metallographic studies were performed on samples in order to determine the changes in the microstructure of the hardened bronze, on the metallographic microscope OLYMPUS GX51 with a digital image analysis, the scanning electron microscope TESCAN VEGA 5136MM with EDX along with the digital recording on the computer. The hardness of the samples was measured by using a Vickers hardness tester at an applied load of one kg. The samples were polished metallographically prior to their hardness measurement. An average of three observations has been considered in this study.

a)



b)

Figure 2 Microstructural features of the as cast aluminum bronze samples showing a dendrite structure and different microconstituents: (a) Primary α; (b) Eutectoid $\alpha+\gamma_2$ (100× and 200×)

3 RESULTS

The study deals with the observations made with regard to the characteristics of the samples as influenced by the type of heat treatment (solutionizing and tempering) parameters (duration and temperature). The results of the chemical composition for aluminium bronze AK2 were: Cu- 78,37%; Al- 10,52%; Fe- 4,44%; Ni- 5,16% and for the AK3 alloy: Cu- 78,95%, Al- 10,97%; Fe- 4,16%; Ni- 4,83%. The response of the samples was assessed in terms of their microstructural features and mechanical properties. The figure shows microstructural characteristics of the as cast Aluminium bronze. It shows a granular structure (50× and 200×). Different microconstituents such as the primary α, eutectoid $\alpha+\gamma_2$ and Fe-rich phase are shown.

Fig. 2 shows a microstructure of the samples solutionized at 950 °C. Solutionizing at this temperature for two hours led to the breaking of the as cast structure and dissolution of the eutectoid and primary precipitates in the matrix forming coarser β.

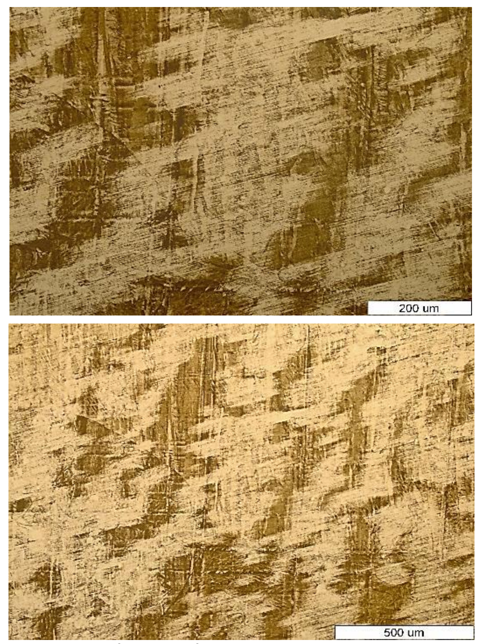


Figure 3 Microstructural features of the aluminum bronze samples solution treated at 950°C for two hrs (200× and 500×)

The microstructures of the samples tempered at 300 °C for two hours are shown in Fig. 3. Tempering at 300 °C for two hrs caused the precipitation of the γ_2 phase in a uniform manner along with some (undissolved) grain boundary precipitates. Increasing the tempering temperature to 400 °C caused a more effective formation of the eutectoid phase, along with a better defined lamellae of the γ_2 phase compared to that at 300 °C.

The heat treated (solutionized and tempered) samples attained a significantly higher hardness than that of their as cast counterpart. The hardness of the solutionized samples tended to increase at the higher temperature (950 °C), while the tempered samples attained the highest hardness amongst all (as cast, solution treated and tempered). Increasing the tempering temperature up to 400 °C led to a decreased hardness. Solutionizing caused the elimination of the as cast structure and microstructural homogeneity along with the formation of a mainly martensite. Increasing the solutionizing temperature of the solution treatment brought about a more effective dissolution of the as cast microconstituents initially and coarsening of the resulting microconstituents at the latter stages. Similarly, tempering brought about the formation of the eutectoid phase at the cost of the previously formed martensite. A rise in the temperature of tempering led the eutectoid transformation to take place more effectively along with the formation of a better defined lamellae of the (eutectoid) phase and dissolution of the grain boundary precipitates. Solutionizing at 950 °C for two hours led the alloy to attain the highest hardness in the category of solutionized samples, while tempering at 300 °C for two hours offered the maximum hardness amongst the tempered samples. The results of the scanning electron microscope with the EDX analysis are shown in Fig. 5.

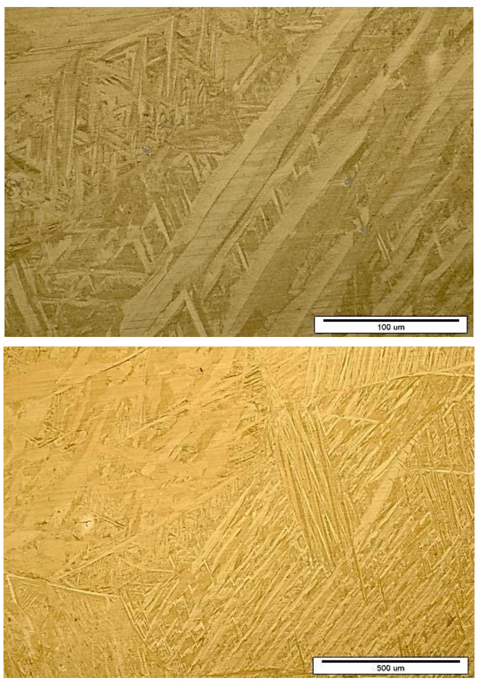


Figure 4 Microstructural features of the aluminum bronze samples tempered at 300 °C for two hours (100× and 500×)

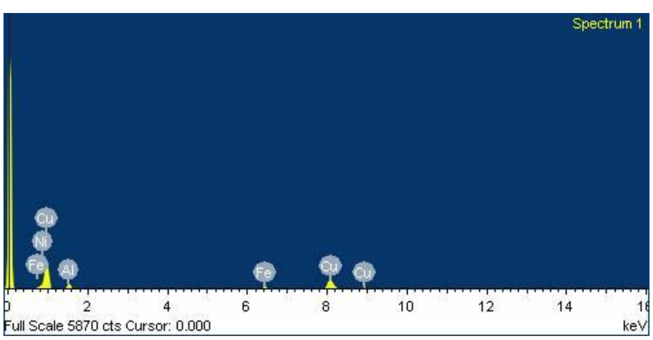


Figure 5 EDX analysis of the examinated alloy

4 DISCUSSION

The microstructural features of the as cast Aluminium bronzes are controlled by the solidification behaviour of the alloy system and the cooling conditions employed during the alloy preparation. Interestingly, equilibrium phases (according to Cu-Al phase diagram) are formed at slow cooling rates such as 500 °C per hour (sand casting of thick sections). Accordingly, the equilibrium of a cast structure comprises of a primary α phase, eutectoid $\alpha+\gamma_2$ and Fe-rich phases (Fig. 2). However, the cooling rates much higher than that of the equilibrium one are generally experienced in practice. This leads to the generation of martensite or bainite depending on the rate of cooling. The presence of Fe leads to microstructural refinement, improved thermal stability, superior mechanical properties through precipitation hardening, restricted growth of grains at high temperatures [6] and a suppressed formation of the unwanted $\alpha+\gamma_2$ phase; the γ_2 phase is hard and brittle and produces embrittlement in the alloy system [7]. Fe-rich particles (Fig. 3) are formed in the temperature range of 350-400 °C [8]. Furthermore, 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 α - phase. This enables Fe to stabilize the α phase and hence suppress the martensitic transformation and favour the formation of bainitic structures [7]. During solutionizing, heating to above 950 °C leads to the generation of 100 % β. Most of the β phase is built up after a few minutes (Fig. 3) at the solution temperature. Prolonged soaking at this temperature leads only to minor changes in the direction of the equilibrium state [8]. The diffusion rate of Al in the β phase is much higher than in the α phase [8]. Accordingly, if there is an α-phase in the structure, there will be no grain growth. Only after a complete dissolution of the α phase does a rapid growth in the grain size occur (Fig. 2) by producing grain sizes in the region of a few millimetres [8]. In complex alloys containing Fe, the solution-treatment temperature has been found to have a significant influence. An increase in the solutionizing temperature leads to the dissolution of more particles; hence higher strength and lower ductility are achieved after subsequent cooling [8]. Holding below ~950 °C results in an increasing amount of β co-existing with α and therefore the quenched alloy has an increasing amount of soft α present. The characteristics of Aluminium bronzes are sensitive to their microstructural features and chemical compositions. The type and parameters employed during the heat treatment also greatly control their microstructural features. Higher hardness of the solutionized alloy samples than that of the as cast specimens could be attributed to the structural homogenization and solid solution hardening and strengthening as also agreed by the formation of martensite or bainite as a result of quenching after solutionizing. Furthermore, higher hardness of the tempered alloy compared to that of the solutionized samples could have resulted from the precipitation of the eutectoid $\alpha+\gamma_2$, which is harder than that of the martensite or bainite formed after solutionizing (Fig. 4). 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 γ_2 phase. Moreover, a reduction in hardness at an increasing tempering temperature was a result of the coarsening of the eutectoid phase. It has been suggested that even though the eutectoid phase is harder than that of the β (martensite), the large amount of primary α may make the alloy softer even after the formation of the eutectoid phase. The properties of the Cu-Al alloys containing a primary α depend on the grain size and shape of the primary α phase. Moreover, coarser primary α grains reduce the strength and ductility significantly despite the identical hardness values. Rapid cooling from a temperature below the eutectoid one causes the formed structure to offer the minimum strength and a low ductility. The highest strength at a low ductility in a quenched alloy is caused by the formation of the martensite phase. Higher hardness is observed with increasing tempering temperatures from 300 °C to 400 °C in Cu-Al-Fe alloys due to the precipitation hardening. Aluminum bronze attains excellent hardness, tensile and compressive strength at room temperature. From the above detailed discussion, it emerges that the microstructural features of Aluminium bronzes are very much sensitive to their processing steps and associated parameters such as temperature, cooling rate and the 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.

5 CONCLUSIONS

This paper presents conclusions drawn from the results obtained and observations made in this research. The conclusions relate to the microstructural alterations brought about by the heat treatment involving solutionizing and tempering and the corresponding changes in the mechanical properties such as hardness. The conclusions drawn from the research are as follows:

a) The alloy displayed the primary α, eutectoid $\alpha+\gamma_2$ as well as the 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. The coarsening of phases was also observed, especially at higher temperatures and durations of the treatment. Tempering caused the formation of the eutectoid phase, along with the retained/untransformed martensite and microconstituents displayed α. Tempering at 400 °C led to the transformation of martensite into the stable eutectoid structure with a better defined lamellae, while the lamellae were not so well defined at 300 °C.

b) The hardness of the samples improved after heat treatment, compared to the one in as cast condition. Solutionizing temperature showed an increase in hardness. Tempered samples attained the highest hardness amongst all. Moreover, the hardness tended to decrease with the increase of tempering temperature up to 400 °C.

The paper suggests that the microstructural features and mechanical properties of the samples get significantly affected by the heat treatment. The type (solutionizing and tempering) 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 the desired combinations of properties through optimizing the heat treatment type and parameters.

Note: This research was presented at the International Conference MATRIB 2017 (29 June - 2 July 2017, Vela Luka, Croatia).

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