A MICROSTRUCTURAL STUDY ON CuSn10 BRONZE PRODUCED BY SAND AND INVESTMENT CASTING TECHNIQUES

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Abstract

Copper based alloys have been used in the industry for a long time because of their good corrosion resistance, high thermal and electrical conductivity, self-lubrication property and good wear resistance. In this study, microstructural characterization of CuSn10 cast bronze samples, produced by sand and investment casting techniques, was carried out. In the first stage of the study, cast alloys were examined by light microscope to determine the matrix phases after metallographic sample preparation. Image analysis was done to determine the secondary dendrite arm spacing having an important effect on the physical and chemical properties of the matrix. In the second stage, macro hardness values of the matrices were measured to reveal the effect on secondary dendrite arm spacing.

Keywords : CuSn10 alloy, casting, microstructure, characterization.

1. INTRODUCTION

The technology of copper alloy founding has advanced considerably in recent years and castings are produced to a high degree of integrity to fulfil many critical applications where inspection requirements are particularly onerous [1].

Bronze materials are widely used as bearing materials for high thermal and electrical conductivity, self-lubrication, good corrosion and wear resistance. Pure copper materials are not used as journal bearing material due to their low mechanical and hardness properties. The tin bronze (90% Cu and 10% Sn) is the most suitable bearing material used under corrosion, high temperatures and high loads [2-4]. They are suitable for handling acidic waters, boiler feed waters, polluted in-shore waters and those contaminated with abrasive sand [1].

Many types of castings can be used for Cu and its alloys, such as sand, shell, investment, permanent mold, chemical sand, centrifugal, and die casting [5]. The technological specifications for casting processes are the most important factors to obtain good results. In this study, microstructural characteristics of CuSn10 bronze alloys manufactured by sand casting and investment casting were compared. Macro hardness of the matrices were measured to reveal the effect of secondary dendrite arm spacing. The increased use of solidification modeling in the casting industry has concentrated on better understanding of the manufacturing process to improve quality. The dendrite arm spacing, macro/microsegregation, distribution and morphologies of precipitates, as well as porosity, all influence the final mechanical properties [6-8].

2. EXPERIMENTAL STUDY

2.1 Material

Tin bronzes may conveniently be divided into two groups: low-tin bronzes and high-tin bronzes. Low-tin bronzes are those in which the tin content is less than 17%. This is the maximum theoretical limit of the solubility of tin in the copper-rich solid solution. In practice, the usual limit of solid solution is nearer to 14%, although it is rare to find a bronze with this tin content in a homogeneous single phase [9]. In this study, a low-tin bronze was selected as the experimental alloy and **Tab. 1** shows its chemical composition. Alloy casting was carried out at an industrial plant. Sand mold and investment casting techniques were used.

Table 1. The chemical compositions of CuSn10 alloy (wt-%).

Alloy	Cu	Sn	Zn	Pb	Ni	P
CuSn10	90.25	9.55	0.06	0.03	0.05	0.06

2.2 Hardness measurement

In order to determine the variation of hardness depending on casting technique, macro Vickers hardness tester was used. After five measurements, the mean macro hardness values of the matrices were determined as 87 and 79 HV5 for sand and investment cast samples, respectively.

2.3 Metallographic sample preparation and microscopic examinations

All samples for the microstructural characterization were prepared by grinding with 320, 600 and 1000 mesh size SiC abrasives, respectively and then ground surfaces were polished with 3 µm diamond solution. Etching is required to determine the phases within the matrix and several etchants given in **Tab. 2** were used to reveal the grain boundaries, solidification morphology and secondary phases. Zeiss Axiotech 100 light microscope (LM) was used for metallographic examinations.

Table 2. The composition of the etchants used in the study.

Etchant	Composition
A1	10 g $FeCl_3$, 50 ml HCl, 10 ml HNO_3, 100 ml H_2O
A2	20 ml NH_3, 80 ml H_2O, 1 droplet H_2O_2
A3	5 g $AgNO_3$, 50 ml H_2O
A4	3 g $FeCl_3$, 50 ml HCl, 50 ml H_2O

2.4 Image analysis

Leica QWin software package was used to determine the secondary dendrite arm spacing by means of image analysis. The average and standard deviation values of this spacing were calculated from at least 60 measurements on the images of etched specimen surfaces. The secondary dendrite arm spacing is 31.70 µm for the matrix of sand cast sample, whereas it is 60.26 µm for the matrix of investment cast one.

3. RESULTS

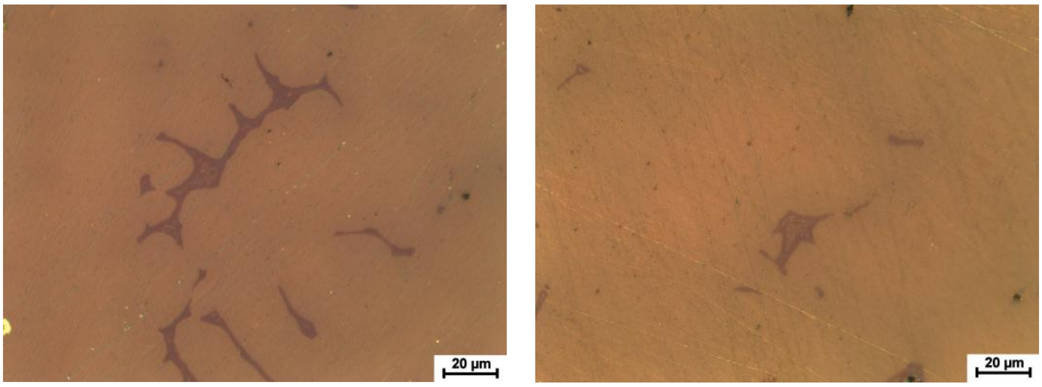
3.1 Microstructural characterization

Eutectoid in the bronze system originates from a complex series of changes and the solidification can be summarized as follows: (i) the alloy passes through the alpha+liquid region as it cools, (ii) it reaches a transition at about 798°C and a peritectic transformation occurs, (iii) a beta intermediate solid solution results, (iv) on cooling to about 586°C, the beta phase transforms to gamma, (v) at 520°C the gamma solid solution transforms to the final solid mixture of alpha+delta eutectoid. When a tin bronze is cast, the alloy is extensively segregated, usually with cored dendritic growth, and an infill of the alpha+delta eutectoid surrounds the dendritic arms. The center of the dendrite arms are copper-rich, since copper has the higher melting point, and the successive growth of the arms results in the deposition of more tin. At low-tin contents, for example, between 2 and 5%, it may be possible for all the tin to be absorbed into the dendritic growth. This varies considerably depending on the cooling rate of the bronze and the kind of casting involved. If the cooling rate is very slow, there is a greater chance of reaching equilibrium, and the amount of interdendritic delta phase will be much reduced or disappear entirely. However, at tin contents of about 10% it is very unusual in castings to get absorption of all the delta phase and the dendrites will usually be surrounded by a matrix of the alpha+delta eutectoid [10].

Fig. 1 shows the microstructures of polished CuSn10 alloys produced by both sand mold and investment casting. Polarization contrast is used to observe the secondary phases (possibly delta phases) in the tin bronze. Those phases within the sand cast matrix are closer to each other than the ones within the investment cast matrix. In sand cast matrix, the secondary phases take place in the interdendritic zones, whereas they are randomly distributed in the investment cast matrix. This indicates that the matrix produced by sand mold casting has finer and a regular dendritic solidification compared to the one produced by investment casting.

The dendritically solidified matrix of CuSn10 alloy after sand mold casting is shown in **Fig. 2a** and **Fig. 2b**.The term dendrites refers to the branched tree-like solid spikes which propagate into the liquid during the solidification of supercooled pure metals or supersaturated alloys. In many metallurgical processing techniques the formation of dendrites plays a vital role in the quality of the final product. Since complex shapes can be readily produced and further expensive production steps are avoided, casting of alloy parts and components offers distinct cost cutting advantages over other metal forming methods. In many commercial alloys, microstructural features that determine the mechanical integrity of a cast ingot, such as solute segregation, grain size and porosity, all depend critically on the morphologies and velocities of individual or arrays of growing dendrites [11].

In bronzes, the eutectoid constituent is made up of two phases, alpha (the copper-rich solid solution of tin in copper) and delta (an intermetallic compound of fixed composition, $Cu_{31}Sn_8$). This eutectoid phase begins to appear in the microstructure between about 5% to 15% tin (and above), depending on the cooling conditions of the alloy. It is a light blue, hard and brittle material that often has a jagged appearance. The structure is shaped by grain boundary edges and the blue delta phase often contains small islands of alpha phase dispersed through it [10]. **Fig. 2c** shows these eutectoid phases as massive precipitates in the matrix. The grain boundaries are the regions where the precipitation is thermodynamically promoted. In **Fig. 2d**, a typical delta phase is observed that takes place at the grain boundary. For a given material, it is an undesired formation since it weakens the mechanical properties.



(a) (b)

Figure 1. The microstructures of polished CuSn10 alloys produced by (a) sand mold and (b) investment casting technique.

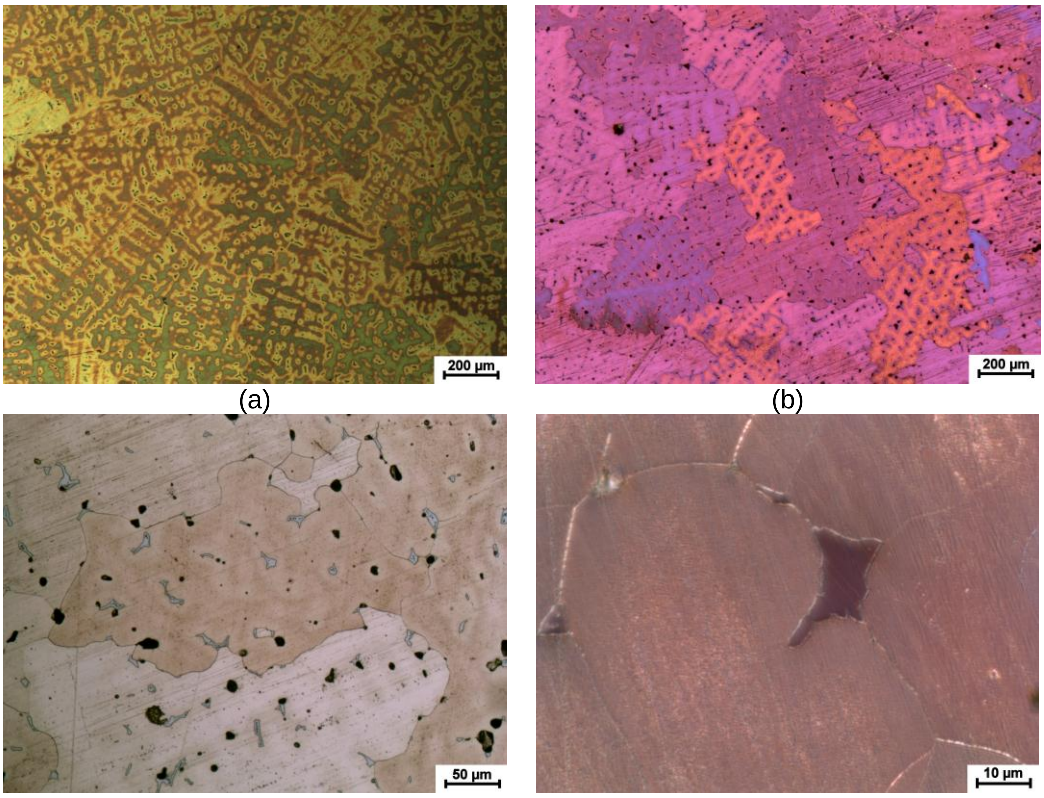
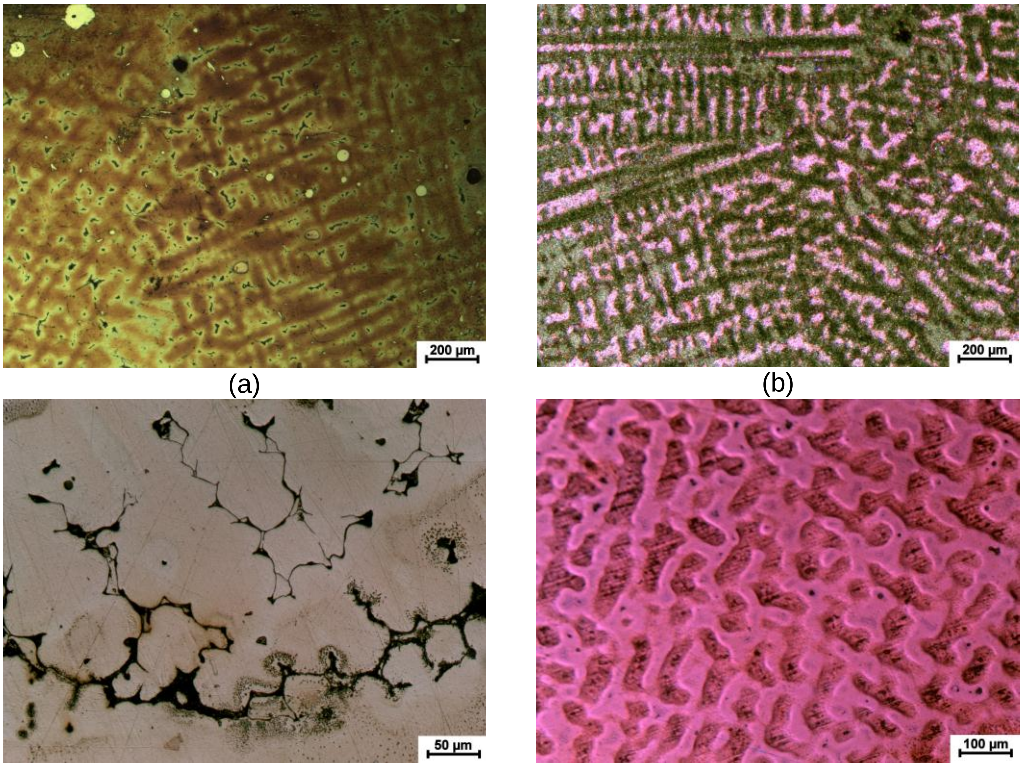


Figure 2. The microstructures of etched CuSn10 alloy produced by sand mold casting technique; (a) etched by A1 solution, in brightfield contrast, (b) etched by A1 solution, in polarization contrast, (c) etched by A2 solution, in brightfield contrast, (d) etched by A2 solution, in polarization contrast.

In the case of the investment casting process, the investment shell is kept at an elevated temperature during pouring, which increases the local solidification time. Whilst fine grains can be obtained in investment cast components through the proper additions of nucleating agents, the dendritic arm spacing tends to be larger. Thus, in order to improve the mechanical properties of components made by the investment casting process, there is a need to refine the dendritic arm spacing of these castings [12]. The structure within a grain consists of a large number of dendrite arms which grow from the same initial growth point and have identical crystallographic orientation. Thus each grain is accepted as containing a single dendrite. The main stems are called the primary dendrite arms. In columnar grains the primary dendrite arms are roughly parallel to the heat flow direction. Arms branching out from the primary arms are termed secondary arms. The effects of solidification conditions on dendritic structure are best measured using dendrite arm spacing parameters. Perpendicular distances between primary, secondary and higher order branches provide these parameters [13].

Fig. 3 shows etched microstructures of solidified matrix of CuSn10 alloy produced by investment casting technique. A typical dendritic morphology in the matrix is seen in **Fig. 3a**. The dendritic structure is relatively coarser than the one produced by sand mold casting and it exhibits a directional solidification. Some of the metals (i.e. high-tin bronzes) themselves also give rise to colored effects under polarized illumination if they are optically anisotropic, namely if they have two or three principal refractive indices [10]. The length and coarser part of the dendritic structure are shown in **Fig. 3b** with the polarization contrast. Etching by a mixture of ammonia and distilled water (A2 solution) reveals the grain boundaries and the precipitates at the boundaries. **Fig. 3c** shows the secondary phases (intermetallics of $Cu_{31}Sn_8$) having dark contrast and precipitated at the grain boundaries. **Fig. 3d** indicates the coarser dendiritic structure of the matrix.

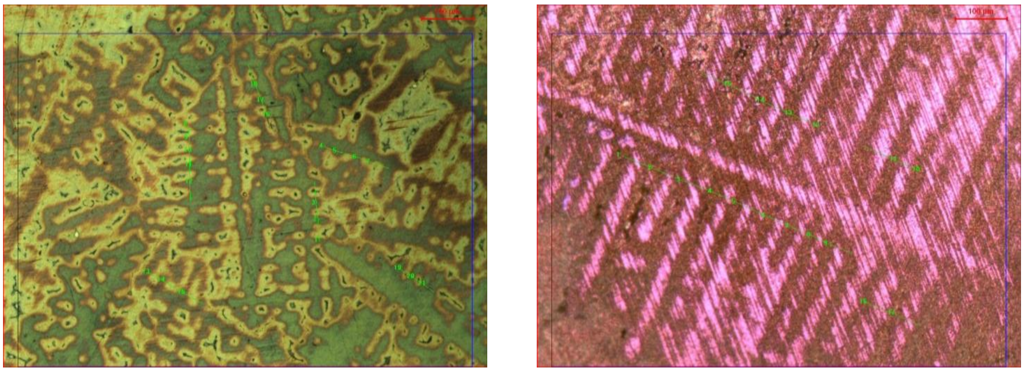


(a) (b) (c) (d)

Figure 3. The microstructures of etched CuSn10 alloy produced by investment casting technique; (a) etched by A1 solution, in brightfield contrast, (b) etched by A3 solution, in polarization contrast, (c) etched by A2 solution, in brightfield contrast, (d) etched by A4 solution, in polarization contrast.

3.2 Evaluation of secondary dendrite arm spacing

The temperature gradient and the solidification rate determine the form and the scale of the microstructures of an alloy. With increasing temperature gradient and solidification rates, the dendrite arm spacing decreases and a refined microstructure is observed. A reduction of the dendrite arm spacing is equivalent to a more homogeneous distribution of alloying elements and smaller segregation distances [14]. For the experimental materials, the matrix formed by sand mold casting has finer dendritic structure and its secondary arm spacing is lower than the one obtained by investment casting. The dendrites within the sand cast matrix are versatile, however, they grow upwards directionally in the investment cast matrix due to solute redistribution causing segregation during solidification. **Fig. 4** shows the microstures of both castings used for the measurement of secondary dendrite arm spacing.



(a) (b)

Figure 4. The microstructures showing the measurement of secondary dendrite arm spacing in CuSn10 alloy produced by (a) sand mold and (b) investment casting techniques.

4. CONCLUSIONS

In this study, the microstructural characterization of CuSn10 alloy produced by sand mold and investment casting techniques was carried out. It is concluded that (i) both matrices have typical dendritic structure and alpha+delta eutectoid, (ii) the matrix produced by sand mold casting has a finer structure and lower secondary arm spacing than the one produced by investment casting, (iii) the matrix of sand mold casting is harder than the matrix of investment casting due to finer secondary arm spacing.

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