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Effect of Post Cast Heat Treatment on Cu20wt.%Sn on Microstructure and Mechanical Properties

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Abstract

Casting is one method of making metal components that are widely used in industry and up to date. The sand casting method is used due to its simplicity, ease of operation, and low cost. In addition, the casting method can produce cast products in various sizes and is well-suited for mass production. However, the disadvantage of casting, especially gravity casting, is that it has poor physical and mechanical properties.

Tin bronze Cu20%wt.Sn is melted in a furnace, then poured at a temperature of 1100°C into a sand mold. The cast product is a rod with 400 mm in length, 10 mm in thickness, and 10 mm in width. The heat treatment mechanism is carried out by reheating the cast specimen at a temperature of 650°C, holding it for 4 hours, and then rapid cooling. The specimens were observed microstructure, density, and mechanical properties include tensile strength and bending strength.

The results showed that there was a phase change from $\alpha + \delta$ to $\alpha + \beta$ phase, an increase in density as a result of a decrease in porosity and a coarse grain to a fine grain. In addition, the tensile strength and bending strength of the Cu20wt.%Sn alloy were increased and resulted in a more ductile alloy through post-cast heat treatment.

Keywords: Tin bronze, Sand casting, Heat treatment, Microstructure, Mechanical properties

1. Introduction

Copper alloys consist of wrought alloys (C100 - C 799) and cast alloys (C 800-C 999)[1]. Engineering materials, especially bronze alloys, are widely used due to their high elasticity, high thermal conductivity, wear-resistance, and good corrosion resistance[2–4]. Bronze is most commonly used for bearings, clips, electrical connectors, springs, turbines, and blades applications. One of the most well-known copper alloys is the cast bronze alloy (Cu-Sn) tin bronze with the C90500 series.

Tin bronze with a tin percentage greater than 17% is considered high tin bronze, while bronze with a tin content less than 17% is considered low tin bronze [5]. Tin Bronze with a composition of more than 17% Sn is widely used as a musical instrument due to its excellent acoustic properties, forging capability, has high mechanical properties[6–8], and has high fluidity on casting method[9,10]. Tin bronze Cu20wt.% Sn is capable of producing a higher sound intensity (dB) with a low damping capacity. Therefore, it was well-suited to be used to produce gamelan instruments [11]. Tin bronze has been used since the 11th century for church bells[7]. In addition, tin bronze has been used to make trumpets in London, England, since the 17th century, thin-walled percussion instruments[12], and gamelan instruments in Indonesia [11,13].

Casting is the oldest manufacturing process other than forging methods known in human civilization. More than 80% of metal components to date are produced by casting[14]. The casting method has been chosen because it can produce metal components with complex shapes and is suitable for mass products with relatively low costs[15]. Sand molding can be utilized to manufacture both thick-walled and thin-walled products [16]. The disadvantages of sand molding are that it produces a rough surface of the cast product, the formation of porosity[15], and has lower mechanical properties than the forging methods[17,18]. The low mechanical properties from produce with the casting method cause church bells to crack over time[8].

In general, the gravity casting method produces low tensile strength and hardness. This is related to the solidification mechanism of the metal alloy and the entering of air during when pouring process. Sand casting is one of the gravity casting methods commonly used. The sand casting method has a rapid solidification rate. The degree of solidification will affect the formation of the microstructure and mechanical properties of the cast product. By increasing the solidification rate, the time required for atoms to diffuse into a finer dendritic microstructure will be reduced [19]. Mechanical properties, including tensile strength and yield point, deteriorate when the solidification rate decreases [20]. The density of cast products using the sand casting method decreases significantly with increasing porosity[11].

Heat treatment is defined as a combination of heating, holding temperature, and cooling processes. Heat treatment results in a phase transition, which affects the mechanical characteristics of metals. Copper and zinc alloys' mechanical characteristics can be enhanced with heat treatment hardening at 780°C followed by water cooling [21]. Annealing increases the hardness and brittleness of Aluminum Bronze[22]. Annealing Cu(7-25)wt.%Sn at 550°C resulted in a more homogeneous alloy phase with less grain growth[23]. The phase change of the tin bronze alloy refers to the Cu-Sn phase diagram, shown in Figure 1. This study aimed to analyze the effect of post-cast heat treatment on the microstructure and mechanical properties of Cu20wt.%Sn alloy.

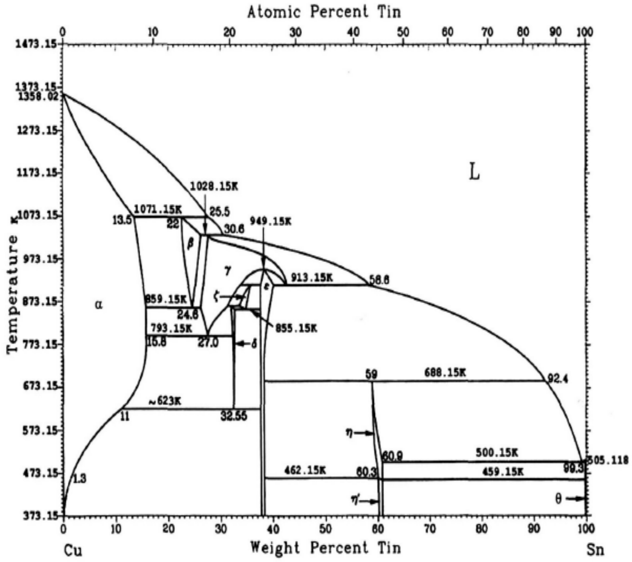


Fig. 1. Equilibrium phase diagram of Cu-Sn [24]

2. Material and method

The materials used in this research are tin bronze Cu=99.9% and Sn=99.9%. The material is melted in a furnace with a pouring temperature of 1100°C. The casting method uses a sand mold. Cast product specimens are rod-shaped with dimensions of 400 x 10 x 10 mm. The composition of the test material is shown in Table 1.

Table 1.
Materials composition

Material	Composition (%)						
	Cu	Sn	Zn	Pb	Fe	Ni	Al
20wt.%Sn	79.77	20.06	0.08	0.02	0.04	0.00	<0.001

The steps of the sand casting method include (a) placing the pattern in a mold, (b) producing a sand mold, (c) pouring molten metal (d) obtaining a specimen of the cast product (e) post-cast heat treatment, shown in Figure 2.

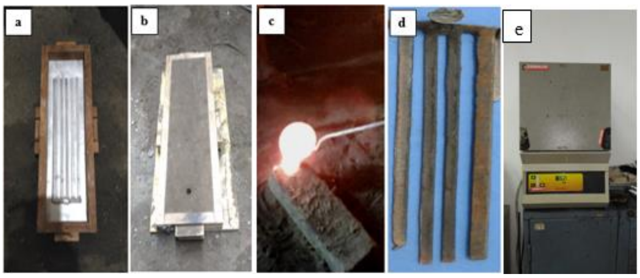


Fig. 2. The steps of the sand casting method

The heat treatment process carried out on post-casting specimens is shown in Figure 3. Heat treatment is carried out by reheating the Cu20wt.%Sn alloy in an electric furnace to the temperature of 650°C. Furthermore, the temperature was held for 4 hours and carried out rapid cooling using water media. Specimen identification is distinguished by giving a code: non-treatment sand casting specimen (SCNT) and post-cast heat treatment specimen (SCHT).

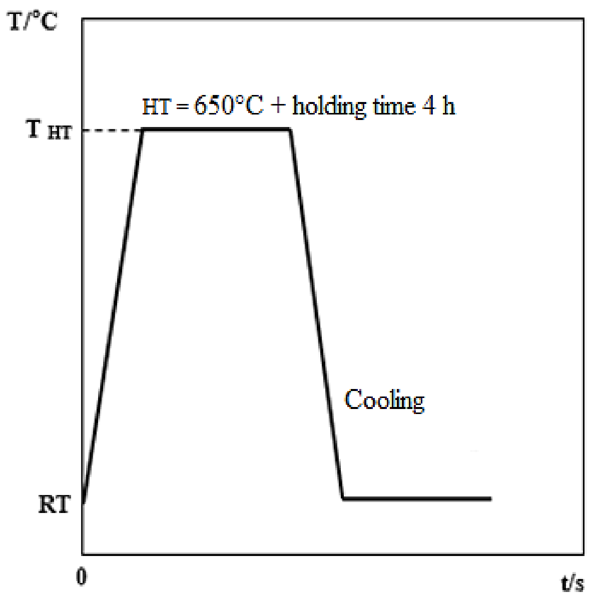


Fig. 3. The heat treatment process

The microstructure was observed using an optical microscope with a magnification of 100X. Previously, the specimen was polished and etched in a mixed solution of HNO_3: H_2O (50% : 50%) for 5 seconds. The density was measured using a rod-shaped specimen measuring 70 x 10 x 5 mm. The density of the tin bronze alloy is calculated using the Archimedes formula, where the actual density ($g.cm^{-3}$) is the ratio between the weight of the specimen in air divided by the difference in value between the weight of the specimen in air and the weight of the specimen in water (g) multiplied density of water ($g.cm^{-3}$). The density is calculated using Equation (1).

$$\rho_b = \frac{w_{air}}{w_{air} - w_{water}} x\, \rho_{air} \tag{1}$$

Where ρ_b is actual density ($g.cm^{-3}$), w_{air} weight in the air (g), water weight in water (g), ρ_{water} pure water density (1 $g.cm^{-3}$).

The microhardness test using the Vickers method (VHN) with a load of 1 N and held for 5 seconds. The tensile strength test follows the ASTM E-8 and ASTM E-290 standards for bending strength with a load of 2 tons. Figure 4. Shows the ASTM E-8 standard for tensile strength tests.

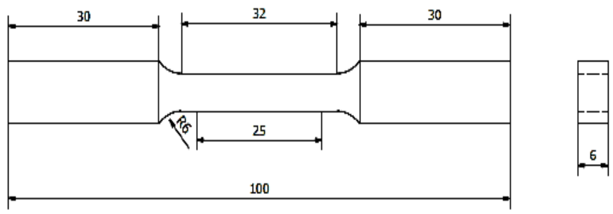


Fig. 4. ASTM E-8 for tensile strength specimen (scale: mm)

The mechanism of bending strength testing with the three-point method is shown in Figure 5.

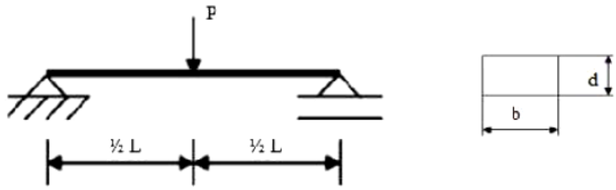


Fig. 5. Bending strength test mechanism with three bending points ASTM E-290

The calculation of bending strength (σb) follows Equation (2), and the calculation of the modulus of elasticity (Eb) follows Equation (3).

$$\sigma_b = \frac{3PL}{2bd^2} \tag{2}$$

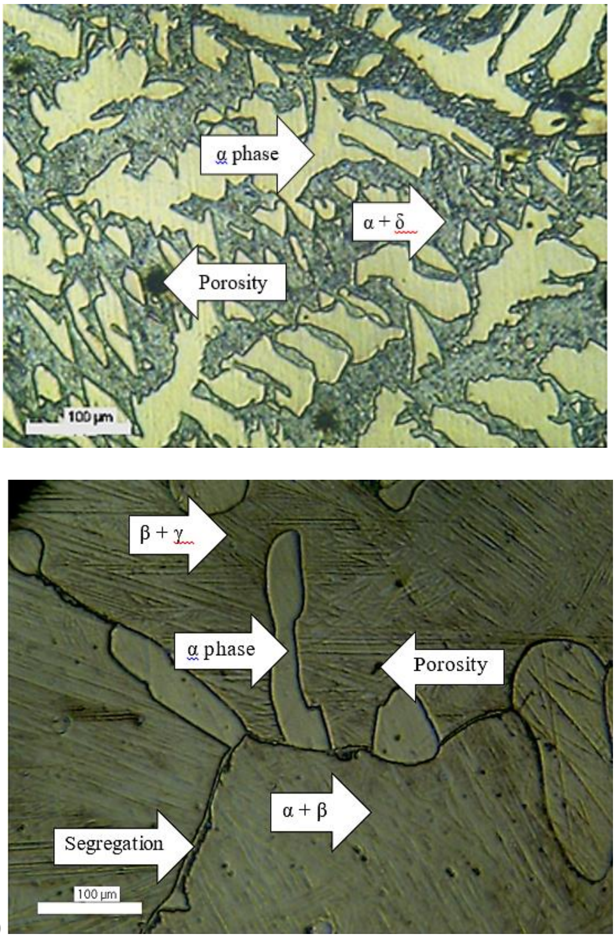
$$E_b = \frac{1}{4}\, x\, \frac{L^3}{bh^3}\, x\, \frac{P}{\delta} \tag{3}$$

Where P is the force in the proportional region (N), L is the distance between support (mm), δ deflection at the mid-point of the specimen for the given force (mm), and b and h the width (mm) and thickness (mm).

3. Results and discussion

The microstructure of the Cu20wt.%Sn alloy through the casting method shows the formation of α + δ phase segregation, coarse grain, and porosity, as shown in Figure 6(a). The mechanism of heat treatment on Cu20wt.%Sn alloy post-casting produces a more homogeneous grain phase characterized by the loss of α + δ phase segregation and the formation of new grains. Heat treatment above the recrystallization temperature will encourage the structure of new microstructures and reduce porosity. Heat treatment at a temperature of 650°C followed by rapid cooling resulted in a phase transition from the α + δ to the α + β phase and fined grains as shown in Figure 6(b). The stages of all phase changes of Cu-Sn alloys through post-casting heat treatment mechanisms refer to the equilibrium phase diagram of Cu-Sn as shown in Figure 1.

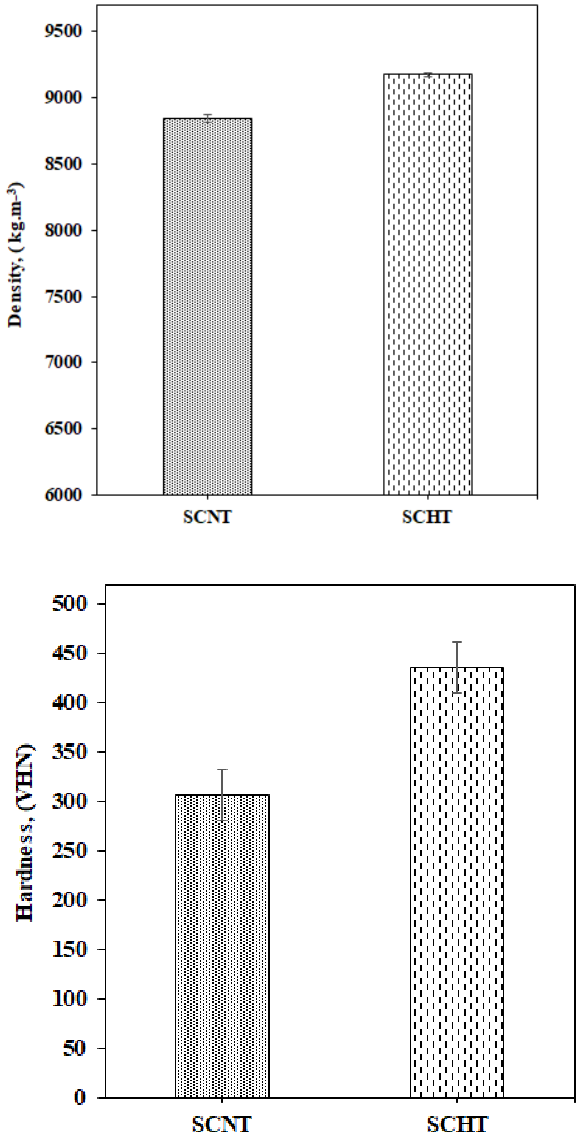
a)



b)

Figure 6. The microstructure (a) Sand Casting Non-Treatment/SCNT (b) Sand Casting Heat Treatment/SCHT

The heat treatment at temperature 650°C with holding for 4 hours followed by rapid cooling can increase the density and hardness of the tin bronze alloy post-casting, as shown in Figures 7(a) and 7(b).



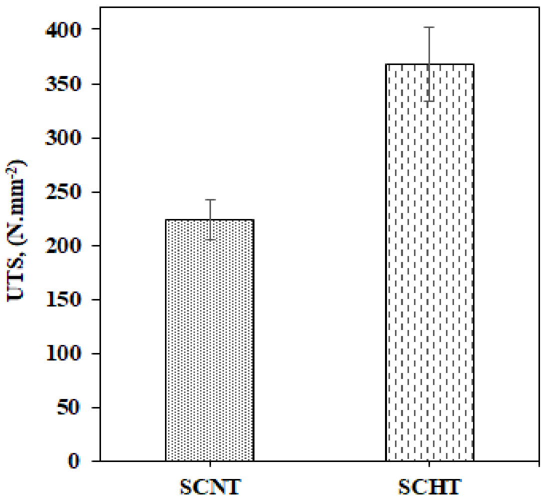
a)

b)

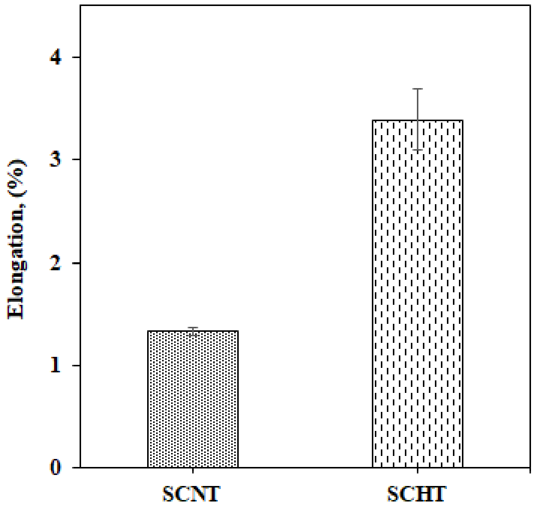
Figure 7. (a) The density Cu20wt.%Sn (b) The hardness Cu20wt.%Sn

The increase in density is due to a decrease in the porosity of the metal alloy. Increased hardness in metal alloys is produced through grain refinement [25]. For example, the hardness of Cu20wt.%Sn alloy through heat treatment (SCHT) process increased by 42.44% from non-treated (SCNT). The increase in the hardness of tin bronze alloys is caused by the increase in grain density, a decrease in porosity, and a fine grain structure with large grain sizes.

The heat treatment process increases the tensile strength, followed by an increase in the elongation of the tin bronze alloy. This is because the phase transition from α + δ to α + β phase results in an increase in grain size and a decrease in segregation at grain boundaries. The phase change for each alloy composition concerning the temperature of the tin bronze alloy is shown in Figure 1. The tensile strength of the Cu20wt.%Sn alloy through the heat treatment process is shown in Figure 8 (a).



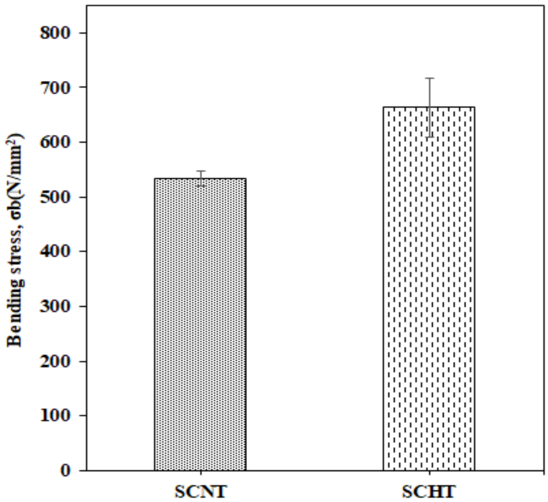
a)



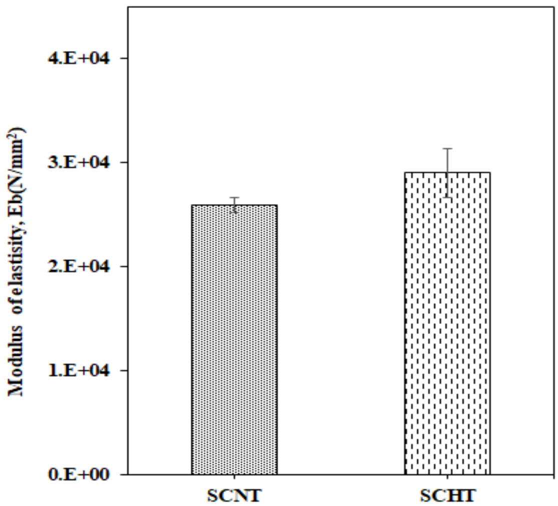
b)

Fig. 8. (a) The tensile strength of Cu20wt.%Sn (b) The elongation of Cu20wt.%Sn

The tensile strength of the Cu20wt.%Sn alloy increased by 64.5% after the heat treatment process. Non-treated cast specimens (SCNT) showed increased elongation after heat treatment. The elongation of cast specimens is increasing through the sand casting method (SCHT) increased by 155.27% after heat treatment. Tensile strength and elongation measurements indicated that the Cu20wt.% Sn alloy was more ductile following heat treatment. This ductile nature is formed from the phase transition from α + δ to α + β and β + γ intermetallic phase. In addition, it also improves the physical properties of density, reduces porosity, and refines grains. The increase in elongation of Cu20wt.%Sn alloy after heat treatment is shown in Figure 8(b).



a)



b)

Fig. 9. (a) The bending strength Cu20wt.%Sn (b) The modulus of elasticity Cu20wt.%Sn

The comparison of bending strength of Cu20wt.%Sn alloy between non-treated and heat-treated is shown in Figure 9(a). The heat treatment given to the post-casting specimens (SCHT) increased the bending strength by 24.30% compared to those non-treated (SCNT). In general, tin bronze Cu20wt.%Sn has improved mechanical properties through post-cast heat treatment. Increased bending strength is the result of a reduction in coarse grains and an increase in fines. In addition, the post-casting heat treatment process can enhance the ductile properties of tin bronze alloys, which are brittle by nature.

The increase in the modulus of elasticity of the Cu20wt.%Sn alloy through heat treatment is shown in Figure 9(b). The modulus of elasticity of Cu20wt.%Sn alloy increases through heat treatment. The increase in the modulus of elasticity is proportional to the bending strength. For instance, post-casting heat treatment (SCHT) increased the modulus of elasticity by 11.87% compared to non-treated (SCNT).

4. Conclusions

Research on Cu20wt.%Sn tin bronze related to post-cast heat treatment concludes:

1. Post-casting heat treatment alters the microstructure of the material, converting small coarse grains to large fine grains and forming segregation at grain boundaries.
2. The alloy undergoes a phase transition from $\alpha + \delta$ to $\alpha + \beta$ and the formation of $\beta + \gamma$ intermetallic phase.
3. The density increases with decreasing porosity, followed by increased mechanical properties, including hardness, tensile strength, bending strength, and modulus of elasticity.

Acknowledgment

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