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Effect of Composition and Pouring Temperature of Cu-Sn on Fluidity and Mechanical Properties of Investment Casting

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Abstract

The composition and pouring temperature are important parameters in metal casting. Many cast product failures are caused by ignorance of the influence of both. This research aims to determine the effect of adding tin composition and pouring temperature on fluidity, microstructure and mechanical properties including tensile strength and hardness of tin bronze (Cu-Sn). The Cu-Sn is widely used as employed in the research is Cu (20, 22 and 24) wt.%Sn alloy using the investment casting method. Variations in pouring temperature treatment T_{S1} = 1000°C and T_{S2} = 1100°C. The mold for the fluidity test is made with a wax pattern then coated in clay. The mold dimensions are 400 mm long with mold cavity variations of 1.5, 2, 3, 4, 5 mm.

Several parameters: increasing the pouring temperature, adding tin composition, decreasing the temperature gradient between the molten metal and the mold walls result in a decrease in the solidification rate which can increase fluidity. The α + δ phase transition to β and γ intermetallic phases decreases fluidity at >22wt.%Sn. The columnar dendrite microstructure increases with the addition of tin composition and pouring temperature. The mechanical properties of tensile strength decrease, hardness increases and the alloy becomes more brittle with increasing tin composition.

Keywords: Tin bronze, Investment casting, Fluidity, Pouring temperature, Mechanical properties

1. Introduction

Tin bronze is an important alloy that is widely used in the metal manufacturing industry. Some use this alloy in the form of machine components such as valves, bearings, pump impellers, piston rings, household, ceremonial equipment, gun components and other mechanical products [1], [2]. Cu-Sn alloys are classified into 2, based on the amount of tin composition. Low tin bronze alloy <17wt.% Sn is used to create various machine components while high tin bronze >17% is used to produce various musical instruments. Tin bronze has been used to make church bells from the 11th century to the present [3-5], trumpets, percussion and gamelan musical instruments [6-8]. The advantages of tin bronze are high strength and thermal conductivity, easy to shape, corrosion resistant, wear resistant, easy to cast and forge and has good acoustic properties [8],[9].

The phase diagram of the Cu-Sn alloy is shown in Figure 1. The Cu-Sn phase diagram is a complex reaction explaining the phase change from the eutectoid phase to the peritectic phase for the heating process and from the peritectic phase to the eutectoid phase for cooling. The explanation of the Cu-Sn alloy phase diagram is limited to the tin composition Cu (13.5-25) wt. %Sn as the main study of this research. There are eight phases in the Cu-Sn binary alloy, namely α, β, γ, δ, η, ε, ξ and the Sn phase. The eutectoid phase (α + δ) is formed at a temperature of 520 °C and the eutectoid phase (α + γ) is formed at a temperature of 586ºC [9]. The peritectic α phase and the β phase can be divided into 2 boundaries, namely: Hypoperitectic from Cα = 13.5%Sn to Cρ = 22%Sn and Hyperperitectic from Cρ = 22%Sn to Cl = 25.5%Sn formed at a temperature of 798°C [10]. At a temperature of 798°C, the formation of the peritectic phase (α+L) and peritectic phase (β +L) initiate at a temperature of 756°C.

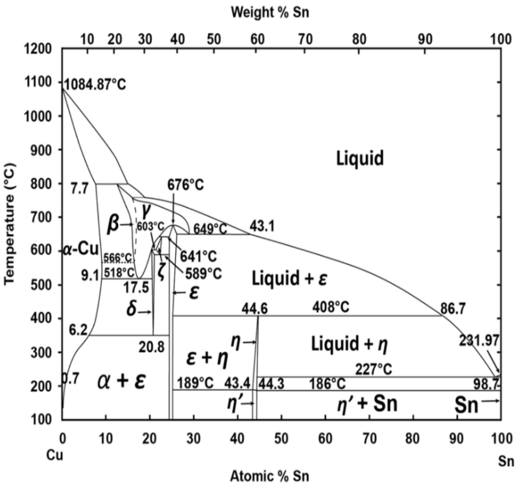


Fig.1. The Cu-Sn phase diagram

Casting method is a metal forming technique that has long been used to make various metal products. One of the metal casting techniques which widely developed is investment casting. Investment casting is better known as the lost wax process or precision casting [11]. The advantages of the investment casting method are the ability to produce cast products attributed thin walls, slopes and curvatures with small radius variations, smooth surfaces, accurate shapes and dimensions [11], [12]. Investment casting produces cast products relative to the final product (close to the net shape), reducing production time and without machining processes [13]. The resulting product does not require final processing on the surface and the product tolerance is high [14]. The disadvantages of investment casting molds are long stage process, relatively expensive, limited to small cast objects and difficult to add cores. Dewaxing and sintering processes are stages that must be carried out in investment casting. This process aims to remove the wax pattern on the mold and stabilize the ceramic mold before usage.

Fluidity is one of the parameters that needs to be considered for the success of metal casting method. Fluidity is the ability of liquid metal to flow and fill each part of the mold [15]. The fluidity length is measured from the pouring point to the end solidification point, namely the maximum distance the liquid metal flows in the mold [16]. Poor fluidity causes difficulty to fill the mold and cast defect to product [17].

The addition of Cu-Sn tin alloy composition can reduce fluidity to a certain extent. Fluidity is influenced by several parameters including alloy composition, pouring temperature and liquid metal viscosity. The addition of tin composition up to 25% Sn increases the viscosity [18], [19]. An increase in the viscosity of the Cu-Sn alloy occurs at a composition of 20-30% Sn in the β and γ intermetallic phases [20].

Increasing the pouring temperature escalates the fluidity length significantly for all types of molds [21]. High pouring temperatures allow the liquid metal to cool for a long time until it finally solidifies. The cooling rate in the investment casting method tends to be slower than in sand molding, inconsequence of the relatively low temperature gradient (ΔT) between the mold and the molten metal [20]. Slow solidification rates produce larger α dendrites and reduce the mechanical properties of hardness and tensile strength of the alloy material [22]. Increasing the pouring temperature to 1200°C deflates the density and mechanical properties of the Cu-20wt.%Sn alloy [23]. Research on Cu (20-24) wt.%Sn tin bronze with microstructural characterization of mechanical properties of hardness, tensile strength and impact using the sand casting method [24], the influence of the mechanical properties of Cu20wt.%Sn tin bronze on the sound of the bell [25]. Characterization of the physical properties of porosity and fluidity of molten metal on pouring temperature using the investment casting method on the mechanical properties of bending strength, elongation resulting from stress versus strain has never been done.

This research aims to study the effect of adding the tin composition Cu (20, 22 and 24) wt. %Sn and pouring temperature T_{S1} = 1000°C and T_{S2} = 1100°C on the fluidity, microstructure, and mechanical properties of tensile strength and hardness of Cu- Sn.

2. Material and Method

The alloy used in the research is Cu (20, 22 and 24) wt.%Sn. This alloy is made by melting pure copper and tin (99.9%) through a weight ratio of each. Fluidity molds are resulted with wax patterns with dimensions of 400 mm in length and mold thickness of 1.5, 2, 3, 4, 5 mm. The surface coating of the wax pattern uses clay slurry that sifted through a 200 size particle sieve to ensure the mold is smooth and even. The design of the fluidity pattern and the investment casting method are depicted in Figure 2 and Figure 3.

The pouring temperature is varied at superheat temperatures T_{S1} and T_{S2}, where T_{S1} = 1000ºC and T_{S2} = 1100ºC. The wax pattern is removed from the mold through a dewaxing process at a temperature of 300-350ºC at once to reduce the water content and harden the mold. The composition of the Cu-Sn alloy was tested using spectrometry and the percentage of each element. The specimen was etched by dissolving a mixture of HNO_3 and H_2O in a ratio of 50%: 50% for 5 seconds. Microstructural observations were executed using a microscope with 100X magnification. Testing of mechanical properties for tensile strength according to ASTM E-8 standards and hardness values using the VHN method. Physical properties including density and porosity are calculated using Equation (1) and Equation (2).

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

$$\text{Porosity (\%)} = (1 - \frac{\rho_b}{\rho_{theory}})\text{ x } 100\% \tag{2}$$

where:
ρ_b = Actual density of the specimen (gr/cm^3),
w_{air} = Weight of specimen in air (gr),
w_{water} = Weight of specimen in water (gr),
ρ_{water} = Density of pure water (1 gr/cm^3),
ρ_{theory} = Theorical density of tin bronze (gr/cm^3).

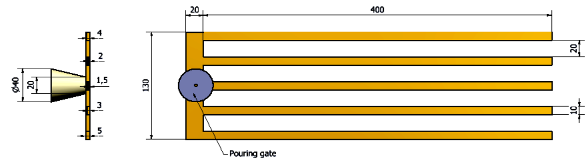


Fig. 2. The design of the fluidity pattern

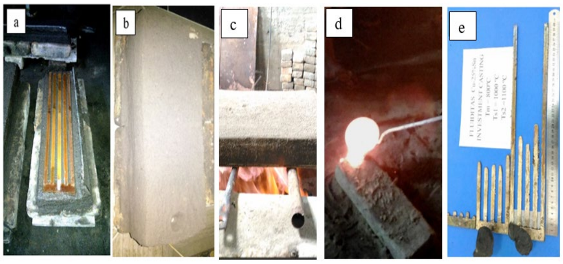


Fig. 3. The investment casting method (a) wax pattern (b) the wax pattern is coated with clay (c) dewaxing the wax pattern (d) pouring the mold (e) fluidity specimen

Tensile strength testing was accomplished by test specimen in accordance with ASTM E-8 as presented on Figure 4.

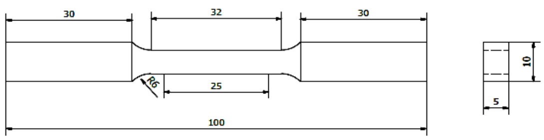


Fig. 4. Tensile strength specimen ASTM E-8

The tensile stress is expressed by Equation 3:

$$\sigma = \frac{F}{Ao} \tag{3}$$

where:
σ = Tensile stress (MPa),
F = Load (N),
A_o = Cross-sectional area (mm2).

Calculation of hardness values uses the Vickers method (VHN) Equation 4.

$$VHN = 1,854 \frac{P}{d^2} \tag{4}$$

where:
VHN = Surface hardness value (kg/mm^2),
P = Indent load (kg),
d = Average diagonal of penetrator (mm).

3. Result and Discussion

Test results for the composition bronze of tin alloy as research material Table 1.

Table 1.
Alloy composition (%)

Sample	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
22wt.%Sn	78.16	21.39	0.03	0.14	0.13	0.10	<0.001
24wt.%Sn	75.13	23.86	0.14	0.20	0.48	0.14	<0.001

The results of fluidity length of the Cu (20, 22 and 24) wt. %Sn alloy using the investment casting method are exhibited on Figure 5.

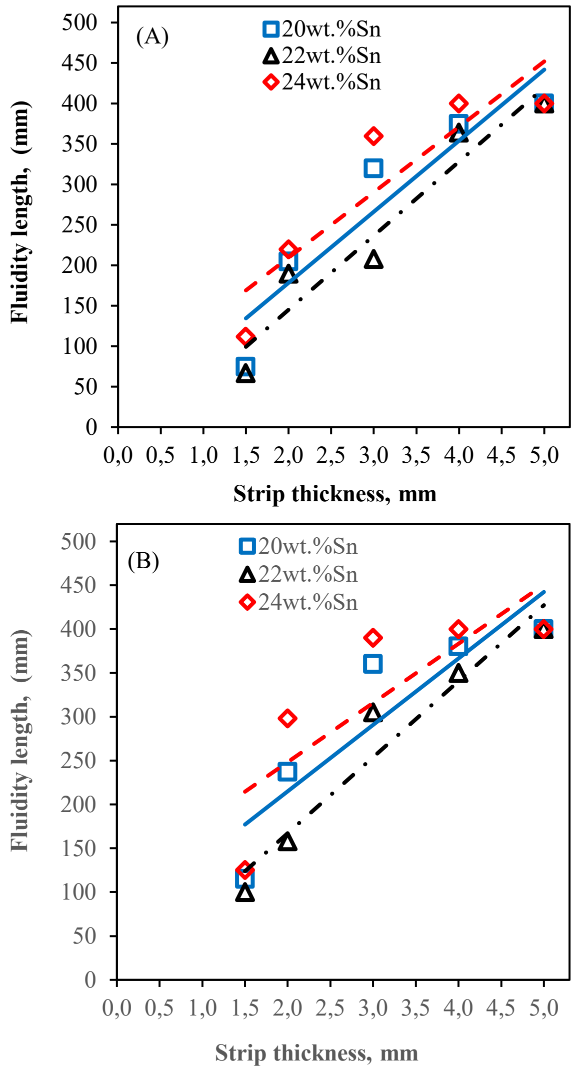


Fig. 5. Fluidity of the Cu (20, 22 and 24) wt. %Sn alloy (A) Pouring temperature 1000°C (B) Pouring temperature 1100°C

Increasing the pouring temperature and adding tin composition causes fluidity to increase. The addition of tin composition enhances the fluidity to a certain extent. Tin composition >22wt.%Sn exhibits a decrease in fluidity. The decrease in fluidity is caused by increasing viscosity linear to tin composition [26]. An increase in the viscosity of the Cu-Sn alloy occurs at a composition of 20-30 wt.% Sn in the β and γ intermetallic phases [20]. The compositions of 22wt.%Sn and 24wt.%Sn are transition phases. The Cu-Sn phase diagram (Figure 1) performs that the α+L phase in the hypoperitectic area has a composition of 13.5-22wt.%Sn and the β+L phase has a composition of 22-25wt.%Sn in the hyperperitectic area. The α phase as phase 1 is dominated by copper metal (Cu) then moves to the β phase as phase 2 and the γ phase as phase 3 with increasing tin (Sn) composition. The fluidity of liquid metal is greatly influenced by the elemental composition in the alloy.

Increasing the pouring temperature increases the fluidity in all Cu-Sn alloy compositions. The addition of tin composition and pouring temperature affects the microstructure of the Cu-Sn alloy [24],[27]. The results of microstructure observations present coarse grains with equiaxed and dendritic structures. The addition of tin composition increases the formation of columnar dendrites. The addition of tin composition enhances the formation of α + δ eutectoid phase dendrite columnar grain structures [27]. The Cu20wt.%Sn alloy exhibits a fine grain structure while the Cu (22 and 24) wt.%Sn alloy resulted a columnar structure with coarse grains [24]. The microstructure of Cu (20, 22 and 24) wt.%Sn alloy and pouring temperature 1000ºC are depicted on Figure 6.

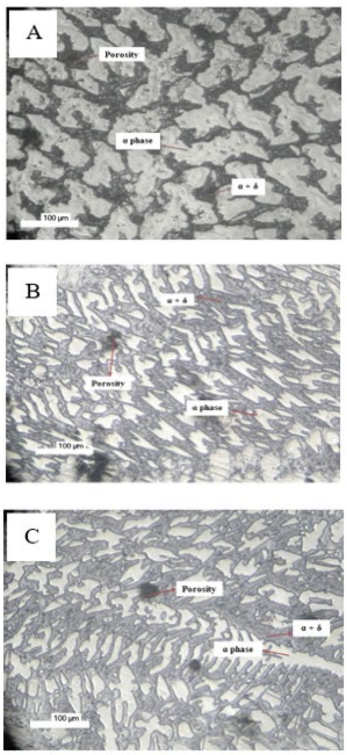


Fig. 6. Microstructure at a pouring temperature of 1000ºC (A) 20 wt. % Sn (B) 22 wt.% Sn (C) 24 wt. % Sn

The microstructure at a pouring temperature of 1100ºC is shown in Figure 7.

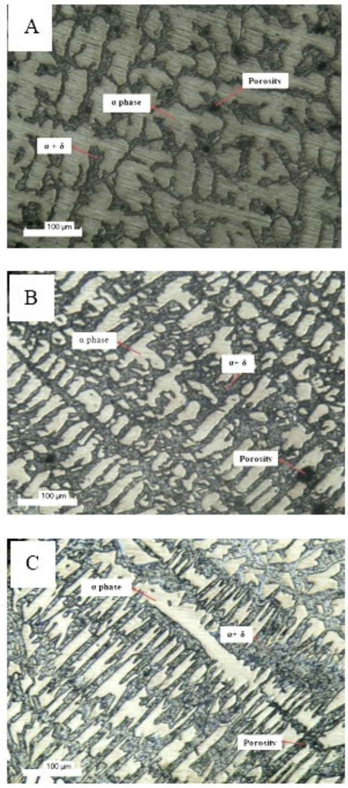
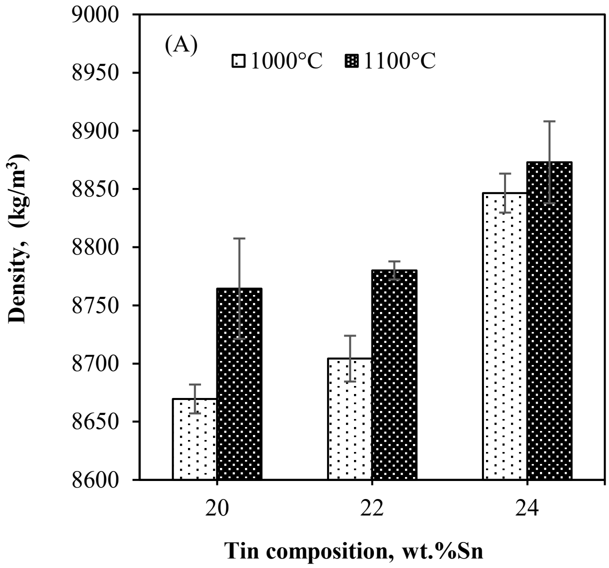


Fig.7. Microstructure at a pouring temperature of 1100ºC (A) 20 wt. % Sn (B) 22 wt. % Sn (C) 24 wt. % Sn

Increasing the pouring temperature and adding tin composition will increase the formation of the dendrite microstructure. This is caused by the increasing temperature gradient from the liquid phase to the α + δ eutectoid phase with the slow solidification rate that occurs in investment casting.

The mechanical properties of the alloy are greatly influenced by the dendrite arm spacing, macro and micro segregation, deposition morphology and resulting porosity. Increasing the pouring temperature affects the density of the resulting alloy. Increasing the pouring temperature increases the density of the alloy yet reduces porosity. The decline in density is due to the increment in alloy porosity. Porosity is formed as a result of air entering and being trapped in the mold when the metal solidified. Increasing the pouring temperature causes the liquid metal to bind air, characterized by the formation of bubbles in the liquid metal. The air dissolves and enters the mold at the same time as the liquid metal poured. The density of the alloy with the investment casting mold is shown in Figure 8. The decrease in porosity is due to the dewaxing process. Apart from removing wax patterns, dewaxing can also reduce the water content of the clay media in the mold. The dewaxing process will also reduce the temperature gradient between the pouring temperature of the molten metal with the mold walls, thereby reducing the solidification rate.



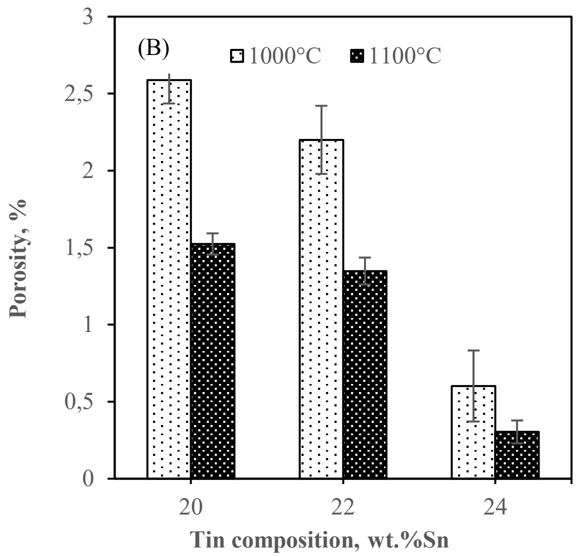
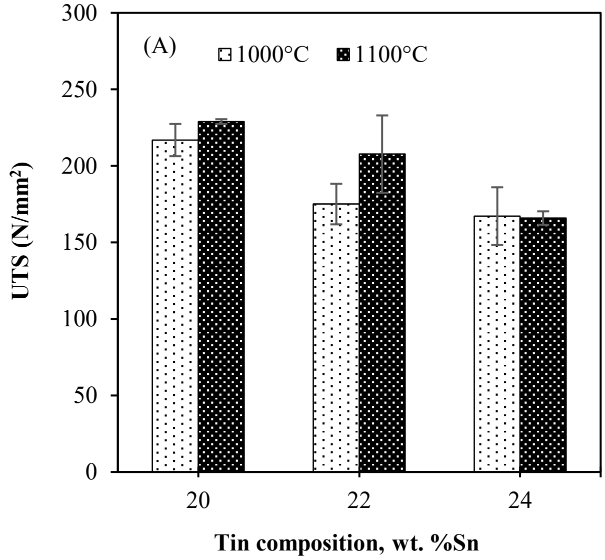


Fig. 8. Mechanical properties (A) Density of Cu-Sn (B) Porosity of Cu-Sn



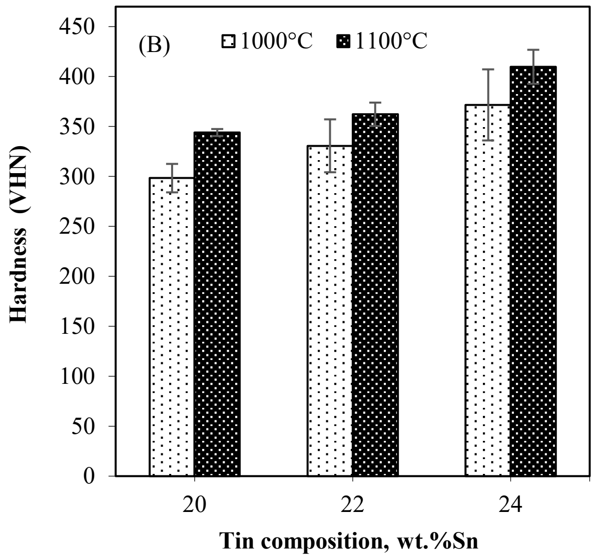


Fig.9. Mechanical properties (A) tensile strength of Cu-Sn (B) hardness of Cu-Sn

The mechanical properties performed are tensile strength and hardness of the alloy. The tensile strength and hardness values of the Cu-Sn alloy with variations in composition and pouring temperature are shown in Figure 9. Reducing porosity has no impact to increase the mechanical properties of tensile strength, this is because the addition of tin composition up to 24 wt.% Sn increases the brittleness of tin bronze.

Figure 9. Defines that adding tin composition reduces the tensile strength of the Cu-Sn alloy for pouring temperatures of 1000ºC and 1100ºC. The decrease in tensile strength is influenced by the reduction in the ductile copper metal matrix, while the tin metal element is soft. The mechanical properties of Cu-Sn alloy are strongly determined by grain shape, microstructure and physical properties, both density and porosity distribution. Meanwhile, adding tin composition increases the hardness value of the Cu-Sn alloy. The decrease in tensile strength and increase in hardness are caused by the formation of relatively coarse Secondary Dendrite Arm Spacing/SDAS with a large grain size [24]. The tensile strength decrease as the grain size increases, as stated in the Hall-Petch Law Equation (5).

$$\sigma_y = \sigma_o + k_y d^{-1/2} \quad (5)$$

d is the average grain diameter, σ_o and k_y are the material particle constants.

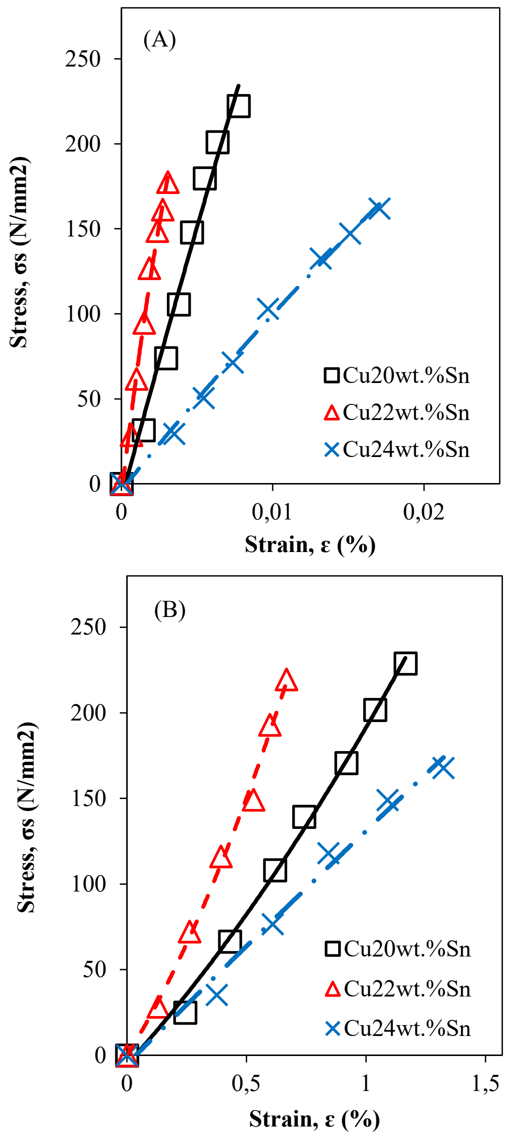


Fig.10. Changes in strain versus stress in tensile strength testing (A) T_{S1} = 1000°C (B) T_{S2} = 1100°C

The Cu22wt.%Sn alloy results brittle properties with lower stress and strain values compared to Cu20wt.%Sn and Cu24wt.%Sn. While the Cu24wt.%Sn alloy performs a higher strain value, the tensile stress value is lower, shown in Figure 10. Ebrittlement of the alloy is determined by a decrease in the copper composition (α phase) and an increase in the tin composition. which undergoes a phase change (β and γ phases) from hypoperitectic to hyperperitectic. The occurrence of embrittlement is influenced by increasing the pouring temperature and adding tin compoition. Increasing casting temperature causes the formation of air cavities which cause porosity. The dewaxing process in the investment casting method tend to remove the wax pattern while reducing the temperature gradient between the mold and the molten metal. The addition of tin composition causes the ductility of the Cu-Sn alloy to decrease due to the copper matrix reduced.

4. Conclusion

Research on the physical and mechanical properties of Cu (20.22 and 24) wt.%Sn alloy using the investment casting method is as follows:

1. Increasing the pouring temperature, adding tin composition, decreasing the temperature gradient between the molten metal and the mold walls result in a decrease in the solidification rate which can increase fluidity.
2. The addition of tin composition to a limit of 22% shows an increase in fluidity, while >22% shows a decrease in fluidity due to the change in the α + δ phase to the intermetallic phase β and γ.
3. Increasing the pouring temperature and tin composition improves the columnar dendrite structure of Cu-Sn alloy.
4. The mechanical properties of tensile strength decrease, hardness increases and the Cu-Sn alloy becomes more brittle with increasing tin composition.

Acknowledgment

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