Forging process on gamelan bar tin bronze Cu-25wt.%Sn post casting deformation to changes in microstructure, density, hardness, and acoustic properties

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Abstract. Casting and forging are a method of formation to produce gamelan instruments. This study aims to determine the effect of forging deformation on the as-cast gamelan bar to changes in the microstructure, hardness, density, porosity, and acoustical properties of the gamelan instrument. The research material was tin bronze Cu-25wt.%Sn. The casting process uses a sand casting method with a pouring temperature of 1100 °C. The forging deformation process was done by reheating the as-cast gamelan bar at a temperature of 600 °C. The thickness of the as-cast gamelan bar is reduced by 30% after the forging deformation process. The observations on the as-cast gamelan bar show coarse microstructure with large grains, inclusions, and increased porosity. The forged gamelan bar shows finer microstructure, elongated grain, α lamellar, α phase like a plate, and decreased porosity. The hardness of forged gamelan bar increased by an average of 30.3% VHN, density increased by 9.56% and porosity decreased by 95% compared to the as-cast gamelan bar. Acoustic properties show an increase in the natural frequency between the as-cast gamelan bar and the forged gamelan bar are 712.5 Hz and 1058 Hz.

1. Introduction
Copper alloys, especially bronze, began to be known and used for various purposes since the 9th and 10th centuries [1]. Bronze materials were used to make church bells in the 11th century [2], to produce bowl and earthenware equipment in the 12th to 14th centuries. The manufacturing process used at that time was dominated by casting and forging. This is indicated by the microstructure formed by casting with rapid cooling [3]. Alloy between copper (Cu) with tin (Sn) is known as tin bronze. It is widely used for various industrial purposes for many years [4]. Bronze is also used to produce multiple musical instruments. Tin bronze was used to make trumpet musical instruments in England in the 17th century, percussion, and gamelan [5–7].

Tin bronze has strength and heat conductivity is good, machineable, corrosion resistant, wear resistant, easily cast, and forged [8]. Other properties of tin bronze can produce acoustical properties, and appearance is good [2]. This alloy is capable of producing long sound with low damping ability [9].
The advantages of these characteristics make tin bronze widely recommended for musical instruments, including gamelan.

The increase in the amount of tin (Sn) in tin bronze alloys as musical instrument material, especially bells and gamelan influence its mechanical and acoustic properties. 10-20wt.%Sn bronze alloy, 5wt.%Zn, and 1wt.%Sb will increase tensile strength, ductility, hardness, and acoustic properties. Addition of other elements of more than 1.5wt.%Pb, Zn, and 1wt.%Ag in this alloy decreases acoustic quality [2]. The alloy of tin bronze with a composition of 20 - 25wt.%Sn produces a high frequency in bells and gamelan compared to the tin composition of 10-15wt.%Sn [10]. The composition of tin is more than 17wt.% Sn, including the high tin bronze group. The composition is the maximum limit of solubility of tin in copper alloys, although in practice the solubility limit is 14wt.%Sn [11].

Gamelan instruments are produced through the casting process of tin bronze alloy followed by manual forgings. Forging methods can increase the rate of dislocation, which can increase the hardness of alloy material. Fabrication through forging, rolling, and hot press processes can increase product density. The disadvantage of forging techniques is that they tend to produce uneven compaction of material and are limited by the size of the object. Forging techniques leave residual stress on gamelan instruments [12]. The negative effect of residual stress on the gamelan is to reduce sound quality over time and trigger cracking [13,14]. Figure 1 stages of the production process of the gamelan bar.

![Figure 1. The process of producing a gamelan bar.](image)

The gamelan material must be able to produce excellent acoustic properties in addition to having superior mechanical properties. The acoustic properties of the material are strongly influenced by the size, shape, and composition of the material [14], including its density and modulus of elasticity [15]. The decrease in material density may be caused by defects in microstructures, impurities, porosity, thermal effects, and dislocations, which cause uneven pressure [16]. This study aims to investigate the impact of deformation due to the forging process on changes in microstructure, hardness, and acoustic properties of high tin bronze Cu-25wt.%Sn.

2. Materials and methods

2.1 Casting processes

The research material was Cu-25wt.%Sn tin bronze alloy. The composition of research material as shown in table 1.

| Material          | Composition (%) |
|-------------------|-----------------|
| 25wt.%Sn          |                |
| Cu                | 70.71           |
| Sn                | 24.9            |
| Pb                | 3.51            |
| Zn                | <0.05           |
| Ni                | <0.02           |
| Fe                | 0.59            |
| Si                | <0.01           |
| Mn                | <0.005          |
| Al                | 0.041           |

Tin bronze alloy Cu-25wt.% Sn obtained by melting Cu = 99.9% and Sn = 99.9% in the crucible furnace. Tin bronze alloy was poured at a temperature of 1100°C with the sand casting method.
The process of forging the gamelan bar was done by reheating the as-cast gamelan bar at a temperature of 600°C. The process of forging the cast bar was done manually by hitting the surface of the specimen many times. The thickness reduction from the as-cast gamelan bar to the forged gamelan bar is 30%. Figure 2 shows the thickness of the gamelan bar.

2.2 Microstructure and hardness characterization
Specimens of the gamelan bar were cut in a transverse direction for mounting and polishing. The polishing process uses sandpaper with sizes 1000 and 1500 mesh. The surface of the specimen was smoothed with an autosol paste and etched using a mixture of HNO$_3$ and H$_2$O (50% : 50%) dipped for 5 seconds. The microstructure was observed using an optical microscope (Olympus, Japan) with 100X magnification. Hardness data was obtained by the Vickers Hardness Number/VHN method with a load of 10 gram and a holding time of 5 seconds.

2.3 Density and porosity calculations
Density and porosity were investigated on rod-shaped specimens measuring 125 x 27.5 x 5 mm. Density and porosity were calculated using equations (1) and (2).

\[
\rho_b = \frac{w_{air}}{w_{air} - w_{water}} \times \rho_{water} \quad (1)
\]

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

(2)

\(\rho_b\) is actual density (g.cm$^{-3}$), \(w_{air}\) is mass in the air (g), \(w_{water}\) is mass in water (g), \(\rho_{water}\) is pure water density (1 g.cm$^{-3}$), and \(\rho_{theory}\) is the theoretical density of high tin bronze 8.900 g.cm$^{-3}$.

2.4 Acoustic investigation
Investigation of acoustic properties using wavanal software version 1.7 created by Bill Hibbert. Acoustic specimens are made according to ASTM E1876-01 standards with dimensions of 125 x 27.5 x 5 mm [17]. The gamelan bar specimen was hit and the sound produced was recorded in the wavanal software. Figure 3(a) shows the mechanism of acoustic testing in the gamelan bar and figure 3(b) shows acoustic test specimens.
3. Results and discussion

3.1 Microstructure observation and hardness measurement

The microstructure observation in the as-cast gamelan bar specimen showed a large α phase, α lamellar, Cu-Sn intermetallic, and porosity in the Cu matrix, as shown in figure 4. Microstructure formed in casting is influenced by several parameters, including pouring temperature, mold material, composition, and solidification rate. Figure 6 shows the microstructure observation in the as-cast gamelan bar with 100X magnification.

Microstructure observation in as-cast gamelan bar shows the formation of coarse grain structures and the separation between phases α and α + δ. The temperature difference in sand molds with relatively high molten metals causes a rapid solidification rate. This causes the nuclei growth to stop. The composition of tin 25%Sn with pouring temperature of 1100°C can increase solidification time from liquidus phase (L) to solidus + liquidus phase (α + L), as binary phase diagram Cu-Sn.

Porosity occurs as a result of the oxidation process in the gamelan bar. This oxidation is formed as a result of the entry of air into the mold during cast metal casting. Low sand permeability causes the mold to release air gas down, and high pouring temperature also causes the liquid to bind to air gas to increase. The type of porosity can be the porosity of the gas and the porosity of the shrinkage cavity. The shape of porosity is very diverse as the shape of the ball, straight flat, or elongated. The location of porosity is also widespread and erratic, often approaching the surface area of the object. The porosity formed on the cast blade tends to be caused by the gas entering the mold.

The microstructure observations on the forged gamelan bar show finer microstructure and α phase undergoing elongation. The grain structure of the α phase changes from a round shape to a flat shape. The intermetallic Cu-Sn volume decreases at the grain boundary and the formed α like plate structure. The area of porosity in the forging gamelan bar decreases. The process of hot forging causes some of
the dissolved α phases to be marked by increasing phase α + δ. Figure 5 shows the microstructure of the forged gamelan blade at a magnification of 100X.

![Microstructure of the forged gamelan bar](image)

**Figure 5.** Microstructure of the forged gamelan bar (a) longitudinal section (b) transverse section.

The hardness in the as-cast gamelan bar is lower than the forged one. The process of hot forging on the as-cast gamelan bar increases dislocation at grain boundaries, which increases the value of hardness.

![Hardness of bronze Cu-25wt.%Sn](image)

**Figure 6.** Hardness tin bronze Cu-25wt.%Sn.

Fine and relatively small grains have higher hardness than large and coarse grains. It is can increase the area of grain boundaries which to impede dislocation motion [19]. For many materials, the yield strength of grain size is expressed by the *Hall-Petch formula* in Equation (3).

\[
\sigma_y = \sigma_0 + k_y d^{-1/2}
\]

Where \( d \) is the average grain diameter, \( \sigma_y \) and \( k \) are constants for a particular material.

The hardness of the forged gamelan bar increased by an average of 30.3% VHN compared to the as-cast gamelan bar. Figure 6 shows the hardness of the as-cast gamelan bar compared to the forged gamelan bar Cu-25wt.%Sn. Increasing the α plate in the forging process can increase the hardness of the forged gamelan bar.
3.2 Density and porosity measurements
Casting is a process of solidification metals, including core growth, grain structure, phase transformation, and precipitation. This is a parameter that requires good planning to reduce defects and porosity. The density of cast products depends on the ability to reduce porosity and defects. Figure 7(a) shows density of tin bronze Cu-25wt.%Sn forged bar and as-cast bar, while figure 7(b) shows both porosity.

![Figure 7](image_url)

**Figure 7.** Physical properties tin bronze Cu-25wt.%Sn (a) Densitas (b) Porosity.

The decreasing density and increasing porosity of the as-cast gamelan bar are caused more by trapped gas in the sand mold. Increasing the air gas content in the mold due to the high pouring temperature, the air entering during pouring of the molten metal and decomposition of the H$_2$O compound used as a binder of a sand mold. The high temperature gradient between pouring temperature and mold temperature causes air to be trapped and porosity in the sand mold [18].

The forging process causes the material to become more compact; the density increases, the porosity decreases and closes the cavity that can trigger the formation of corrosion. The strength of forging techniques can improve the physical properties of tin bronze Cu-25wt.% Sn. The density of the forged gamelan bar increased by 9.56% and porosity decreased by 95% from the as-cast gamelan bar.

3.3 Acoustical properties measurement
The measurement of acoustic properties aims to obtain a difference in nominal frequency (Hz) of the main partials produced on both bars. The natural frequency spectrum of the forged gamelan bar is 32.6% higher than the as-cast gamelan bar. Table 2. shows the frequency comparison between the as-cast gamelan bar with the forged gamelan bar. This is because the density (ρ) of the forging gamelan bar is higher than that of the as-cast gamelan bar.

The acoustic properties of material include sound velocity (c), impedance (z), and radiation coefficient (R) influenced by density [15]. The forged gamelan bar has a low damping capacity resulting in a higher natural frequency (Hz). The mechanical properties of low hardness and increased porosity in the as-cast gamelan bar produce poor acoustic properties. Figure 8 shows the natural frequency (Hz) in both bars.
Figure 8. Natural frequency (Hz) of the as-cast and forged gamelan bar.

Table 2. The frequencies in (Hz) of the main partials.

| Specimens       | Hum  | Prime | Tierce | Quint | Nominal | Super quint | Octave nominal |
|-----------------|------|-------|--------|-------|---------|-------------|----------------|
| As-casted bar   | 212.5| 312.5 | 412.5  | 512.5 | 712.5   | -           | 1456           |
| Forged bar      | 247  | 447.5 | 647.5  | 747.5 | 1058    | 1558.5      | 2122           |

The wavelength and frequency (Hz) produced between the as-cast gamelan bar and the forged gamelan bar as shown in figure 9.

Figure 9. Waveform and frequency analysis (Hz) (a) casted gamelan bar (b) forged gamelan bar.
4. Conclusion
The study of Cu-25wt.% Sn bronze tin can be concluded that the forging process changes the microstructure of the α phase with large and coarse grains in casting to the flat α phase, elongated grains, α like plates and the intermetallic movement of Cu-Sn at grain boundaries. The forging process increases density and reduces porosity in the as-cast gamelan bar. The hardness of the forged bar increased by 30.3% VHN, and the natural frequency (Hz) increased by 32.6%. This increase can produce long sounds with low damping. The forging process can be applied to improve the mechanical and acoustic properties of Cu-25wt.% Sn alloys on gamelan instruments.

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