STM JOURNALS

Journal of
Materials & Metallurgical Engineering

https://journals.stmjournals.com/jomme/

ISSN: 2231-3818 (Online)
ISSN: 2321-4236 (Print)
Volume 14, Issue 2, 2024
May–August
DOI (Journal): 10.37591/JoMME

Review JoMME

Microstructural and Mechanical Characterization of Brass and Bronze Alloys

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Abstract

Brass, a copper and zinc alloy, is renowned for its malleability and resistance to corrosion, making it ideal for musical instruments and plumbing. Aluminium-bronze, which contains copper and aluminium, offers superior strength and wear resistance and is commonly used in marine and industrial applications owing to its durability and corrosion resistance. This study aimed to compare the micro- and macrostructural characteristics of brass and aluminium-bronze alloys. The microstructures of these specimens were examined using an optical microscope equipped with image analysis software, allowing for the detailed visualization and identification of various phases within the materials. This initial microstructural analysis revealed distinct differences in the phase compositions of brass and aluminium-bronze, providing a foundation for further investigation. In addition to the optical microscopy results, more images were taken using a scanning electron microscope (SEM). A Universal Testing Machine was used to perform tensile testing on the specimens to assess their mechanical properties. This testing provided comprehensive data on the modulus of elasticity, stress-strain behavior, yield strength, and ultimate tensile strength of both brass and aluminium-bronze. These mechanical properties are critical for understanding how each material behaves under stress and can inform their potential applications. Pin-on-disk wear tests were conducted to assess the wear resistance of the materials. The results indicated that aluminium-bronze exhibited higher wear resistance than brass, making it more suitable for applications where durability is essential. Additionally, the wear rate for both materials increased with higher test loads, highlighting the importance of considering load conditions in practical applications. Overall, this comprehensive study provides valuable insights into the microstructural and mechanical characteristics of brass and aluminium-bronze, contributing to the understanding of their suitability for various industrial applications.

Keywords: *Microstructural and macrostructural properties, brass, aluminium bronze*

INTRODUCTION

Copper occurs naturally in a form that can be used directly without requiring extraction from an ore, making it one of the few metals with this property [1]. This discovery has led to its use by humans as early as c. 8000 BC. In addition, it was the first metal to be smelted from its ore (approximately 5000 BC), formed into a shape using a mold (approximately 4000 BC), and alloyed with tin to produce bronze (approximately 3500 BC) [2]. In the United States, CuS ores typically contain approximately 1% Cu. Smelting copper sulfide concentrates produces a dull mixture of copper and iron sulfides, which are then melted again in a converter. The remaining sulfur was oxidized by blowing air through the mattes, leaving behind blister copper, which was approximately 99% pure. The fire refining of blister copper further removes impurities, resulting in tough-pitch copper of approximately 99.5% purity, which is suitable for many alloys. The electrolytic refinement of tough-pitch copper can yield an even higher purity (99.9%) for certain applications [3].

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Received Date: July 10, 2024
Accepted Date: August 04, 2024
Published Date: August 10, 2024

Citation: M. Kalyan Phani. Microstructural and Mechanical Characterization of Brass and Bronze Alloys. Journal of Materials & Metallurgical Engineering. 2024; 14(2): 28–37p.

Copper-based alloys are identified using a standardized numbering system developed by the Copper Development Association, which has been adopted by various organizations, including the American Society for Testing and Materials, the Society of Automotive Engineers, and the U.S. government. Alloys 100 to 190 consisted mostly of copper with less than 2% alloy addition, while numbers 200 to 799 refer to the other wrought alloys. The 800 and 900 series include all casting alloys [4].

The most important Cu alloys used in commercial applications can be categorized as follows [5]:

1. *Brasses* - These alloys, which are made of copper and zinc, are further divided into alpha (α) brass with a maximum zinc content of 36%. Yellow alpha brasses have a zinc content of 20-36%, whereas red brasses have a zinc content of 5-20%.
2. *B. Alpha plus beta (α+β) brasses* - containing 36-46.6% zinc. C. Beta (β) brasses - containing 46.6-50.6% zinc.
3. *Bronzes* - These alloys consist of tin and copper and are further divided into A. Bronze tins and B. Bronzes made of silicon. Bronzes made of aluminium D. Copper-nickel alloys.
4. *Cupronickels:* These alloys are composed of copper and nickel.
5. *Nickel silvers:* These alloys contain copper, nickel, and zinc.

Brass

This passage describes brass as an alloy composed of copper and zinc, with varying properties depending on the proportion of its constituents [6]. Brass is a suitable bearing material because of its high corrosion resistance and ease of machining. Zinc has good strength and ductility; however, compared to copper, it has lower thermal and electrical conductivity [7].

Brass is recyclable and non-sparking. In terms of applications, it is commonly used for decoration, making locks, bearings, doorknobs, valves, musical instruments, zippers, fittings, and tools around explosive gases. It is tarnishing-resistant and easily shaped [8].

This paper describes the classification of Cu-Zn alloys based on their Zn content and the phases formed. They explained that alloys with up to 36% Zn are called alpha brasses and have a single alpha-phase, whereas those with 36% to 46.6% Zn are called alpha-beta brasses. Alloys with 46.6% to 50.6% Zn are beta brasses, and those with more than 50.6% Zn are gamma brasses, which are extremely brittle and have no commercial applications except for one containing 50% Zn and 50% Cu used as a brazing solder [9].

Commercial brasses can be classified into two types.

1. alpha brasses or cold-worked brasses
2. alpha-beta brasses or hot-worked brasses.

Aluminium-Bronze

Aluminium-bronze is a type of bronze in which silicon, iron, nickel, manganese, and/or nickel are added to copper as the main alloying metal [9]. Other alloying elements are also added. Figure 1.

Aluminium bronzes exhibit strengths comparable to those of low-alloy steels, adequate ductility to resist fatigue, and exceptional fatigue resistance, thereby making them suitable for marine engineering equipment. They also exhibit excellent resistance to oxidation at high temperatures and are commonly used in applications involving exposure to seawater, such as in the oil and petrochemical industries [10]. Aluminium-bronze is twice as effective as steel in dampening vibrations and can be used to replace gold in dental crown casting [11].

The binary equilibrium diagram of the copper-aluminium system shows that aluminium-bronze alloys fall into three different series.

They constitute the α series, α+β series, and α+γ2 series, possessing properties that are entirely different [12]. The Cu-rich portion of the Cu–Al alloy system is shown in Figure 2.

Journal of Materials & Metallurgical Engineering
Volume 14, Issue 2
ISSN: 2231-3818 (Online), ISSN: 2321-4236 (Print)

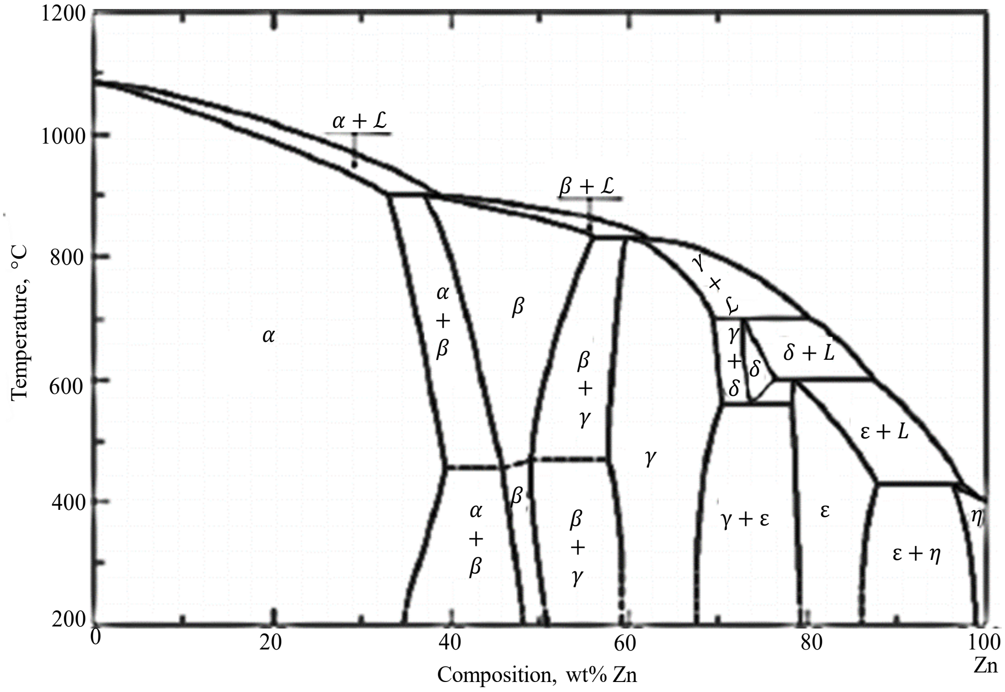

Figure 1. Phase diagram of brass.

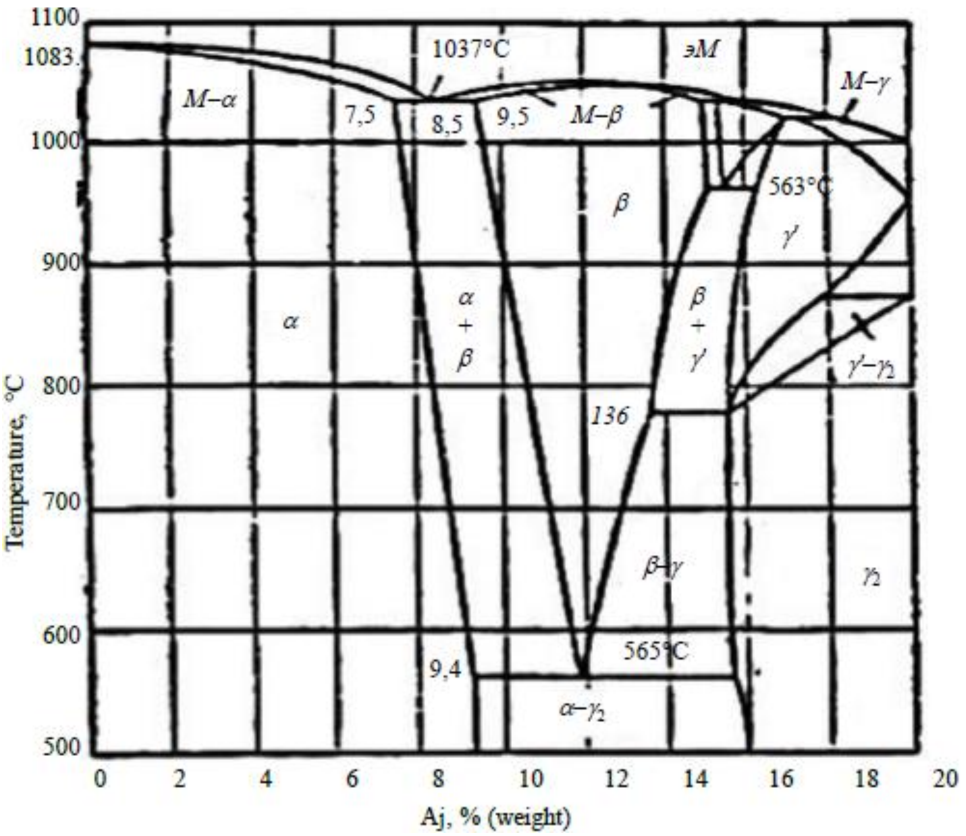

Figure 2. Phase diagram of Al-Bronze.

In this study, aluminium-bronze and brass samples were compared based on their microstructures and mechanical properties and further investigated using metallographic and mechanical testing methods.

EXPERIMENTAL METHODS

Material and Method

The Cu54Zn42 material, which is a brass sample with chemical compositions given in Table 1, and the Cu84Al11 material, which is a bronze sample with chemical compositions given in Table 2, were used for the analysis. Samples of brass and aluminium-bronze were prepared to examine their microstructures. The process of preparing the specimen is crucial for analyzing the microstructure, as the optical microscope relies on the reflection of light from the specimen to generate an image of the metal structure. The microstructures of the brass and aluminium-bronze were examined using a Daheng software-controlled optical microscope. Prior to the analysis, the specimens underwent a series of preparations, including sectioning and grinding using emery paper of varying grit sizes. It was then polished using an ultrafine polishing cloth and a polycrystalline diamond suspension with ethanol solvent with particle sizes of 3 and 1 µm. A chemical etching process was performed using acidified ferric chloride composed of 10 g of ferric (II) chloride, 50 ml of HCl, and 200 ml of water, which was swabbed onto the specimen for 6 s before being examined under an optical microscope. Images of the microstructure were captured at different magnifications, including 100X, 200X, 500X, and 1000X.

SEM analysis was then conducted at high magnification to produce high-resolution images and allow for the measurement of very small features and objects. Surface observations using a scanning electron microscope were performed at 30 kV with a Hitachi-SU3500 Schottky field-emission gun scanning electron microscope equipped with secondary and backscattered electron detectors and an energy-dispersive X-ray spectroscopy (EDS) system to analyze the surface elemental composition. SEM analysis allows for the observation of the external morphology and texture of the sample surface, as well as the chemical composition and orientation of the materials comprising the sample.

Mechanical Testing

Tensile Testing

A basic and frequently used engineering test for determining material properties, including ultimate strength, yield strength, percentage elongation, percentage area of reduction, and Young's modulus, is the uniaxial tensile test [13].

These parameters are essential in the selection of engineering materials for various applications. A standard tensile specimen with specified dimensions is subjected to a longitudinal or axial load at a predetermined extension rate until failure [14].

The applied load and extension were recorded to calculate stress and strain, respectively. Professional associations, such as ASTM, British Standard, JIS, and DIN, offer several universal standards, each with a separate test standard appropriate for a given material, size, and production history [15].

Depending on the standard used, a standard specimen is usually machined into a round or square piece along the gauge length, as indicated in Figure 3(a) and (b), to prepare it for the tensile test. For testing, the specimen ends should be sufficiently long and have a sufficiently smooth surface to allow solid gripping. Any heat treatment should be applied prior to machining to avoid the formation of surface oxide scales, which could serve as stress concentrations and may have an impact on the final tensile properties by causing premature failure.

Table 1. Chemical composition of brass.

Element	Cu	Zn	Fe	Pb	C	O
%	53.87	41.62	0.26	0.94	02.86	0.45

Table 2. Chemical composition of Al-bronze.

Element	Cu	Al	Fe	Ni	Mn	Si
%	83.58	11.13	03.72	0.78	0.46	0.03

Journal of Materials & Metallurgical Engineering
Volume 14, Issue 2
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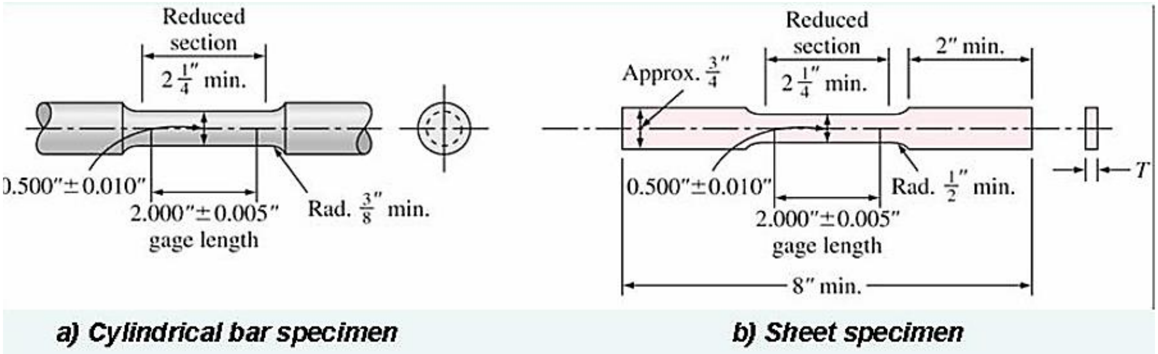

Figure 3. Tensile Specimen Preparation.

Wear Testing on Pin-on-Disk Machine

The interaction between the base and counter bodies can cause wear when there is either no lubrication film or an overly small lubrication film [16]. Wear is a more important phenomenon than friction and lubrication can play a role in reducing friction. Lubrication can also reduce wear because wear is more dominant than friction [17]. A good design can reduce wear, and the wear factor is directly dependent on the design of the component. Measurable wear is the undesirable removal of materials from an operating solid surface [18]. Numerous variables, including load, speed, adhesion and friction coefficients, hardness, and tensile and yield strengths, influence the degree of wear.

The wear rate is affected by factors such as power unit torque and speed, material removal rate, coefficient of friction, and specific energy of the material. The following formula by Archard provides an approximate estimate of how the load (W) and hardness (H) affect the wear rate (Q), where K is the "wear coefficient" of the system and is dependent on several of the elements listed below [19]:

$$Q = KW/H$$

RESULTS AND DISCUSSIONS

Microstructural Study

Microstructure of Brass

As shown in Figure 4(a)–(d), the phase structure of brass is composed of α-phase crystals that precipitate in a β-phase matrix. Bright-field illumination optical microscopy demonstrated that the β phase had greater contrast than the alpha-phase [20]. The size of the interphase boundaries, which is influenced by the size of the α-phase crystals and the β-phase concentration, can be increased to increase machinability. Longer interphase barriers are typically produced by higher beta-phase volume fractions and finer alpha crystals (with a constant alpha-phase content).

This resulted in improved mechanical properties.

Microstructure of Bronze

The phase structure of aluminium-bronze consists of alpha-phase crystals and an iron-rich □□phase precipitated in a beta-phase matrix. Bright-field illumination light microscopy revealed that the β phase had greater contrast than the alpha-phase.

It has a granular structure [21]. Different microconstituents, such as primary alpha-, beta-, and Fe-rich phases, are shown in Figure 5(a)–(d), respectively. The strength of Al-Bronze increases with decreasing alpha-phase content in the microstructure and increasing beta-phase content [22].

The mechanical properties of aluminium bronzes depend strongly on the Al content; between 8% and 12% Al, the alloys are progressively strengthened by the presence of the beta-phase. Iron is the most important alloying element, in addition to Al. Its solubility in Cu was 0.5–1%. Excess Fe strengthened the matrix by precipitating fine particles of Fe3Al-based κ phase. The morphology and amount of these phases significantly affect the mechanical, friction, and wear behaviors of the alloy [23].

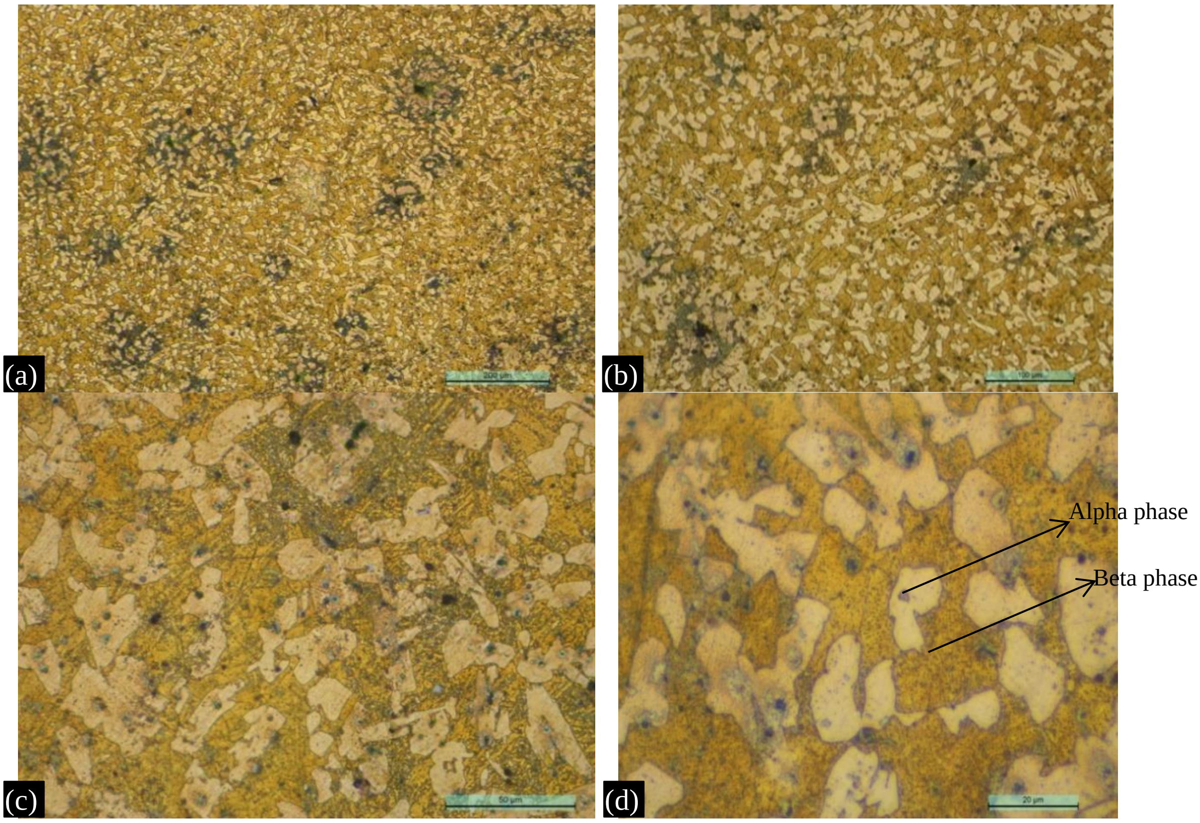

Figure 4. Microstructure of Brass, (a)100X, (b)200X, (c)500X, (d)1000X

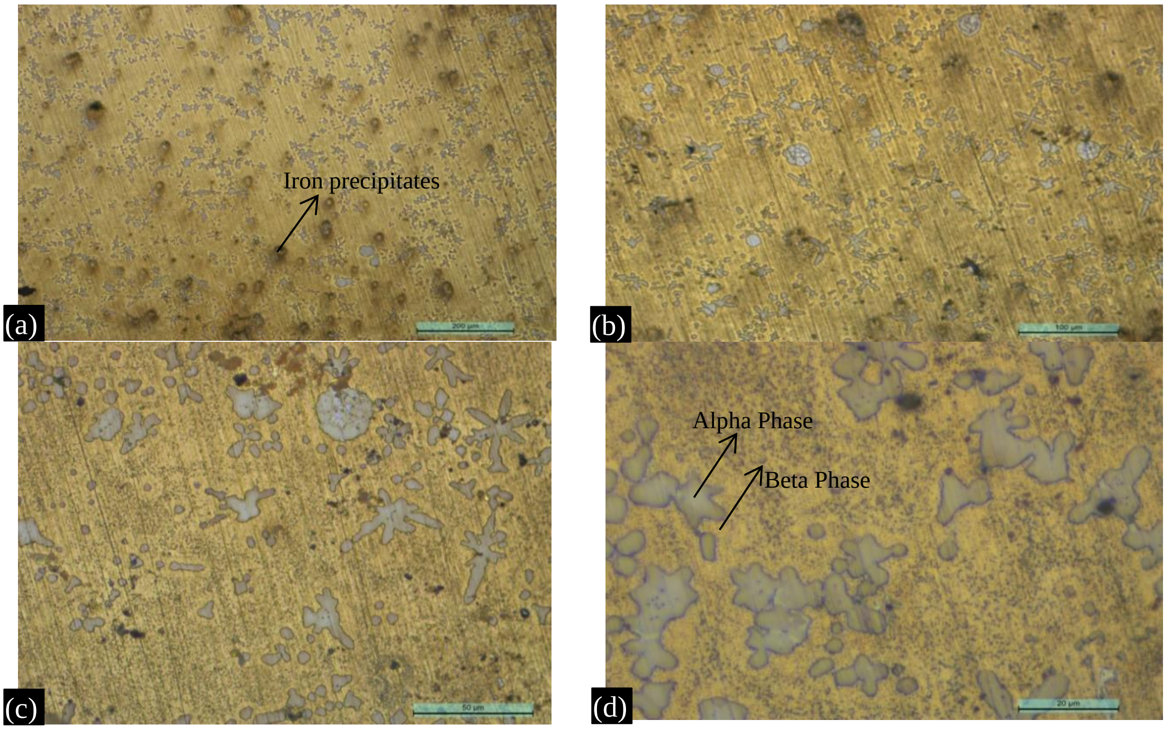

Figure 5. Microstructure of Bronze, (a)100X, (b)200X, (c)500X, (d)1000X

Journal of Materials & Metallurgical Engineering
Volume 14, Issue 2
ISSN: 2231-3818 (Online), ISSN: 2321-4236 (Print)

SEM Analysis

Brass

The SEM images of the brass sample are shown in Figure 6(a) and (b).

Bronze

SEM analysis of the brass sample is shown in Figure 7(a) and (b)

Tensile Test Results

A load versus elongation curve can be used to graphically represent the output obtained from the tensile test, which is recorded as the load versus displacement/elongation. To assess the tensile qualities of the materials, the load versus elongation curve was transformed into an engineering stress versus strain curve. The yield strength, tensile strength, fracture strength, % elongation, modulus of resilience, and modulus of toughness are tensile parameters that can be found in the stress-strain curve.

Brass

Figure 8 shows the tensile stress (MPa) versus tensile strain (%) curve of the brass sample. The tensile properties of the samples were calculated from the curves and are listed in Table 3.

Bronze

Figure 9 shows the tensile stress (MPa) vs. tensile strain (%) curve for the Al-Bronze sample. The tensile properties of the samples were calculated from the curves and are presented in Table 4.

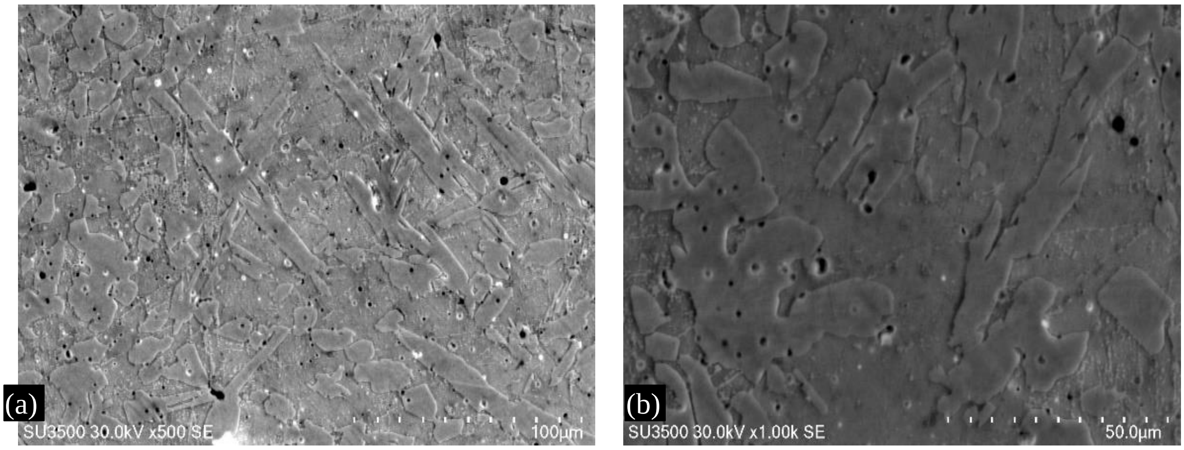

Figure 6. SEM images of brass, (a) 500X, (b) 1000X.

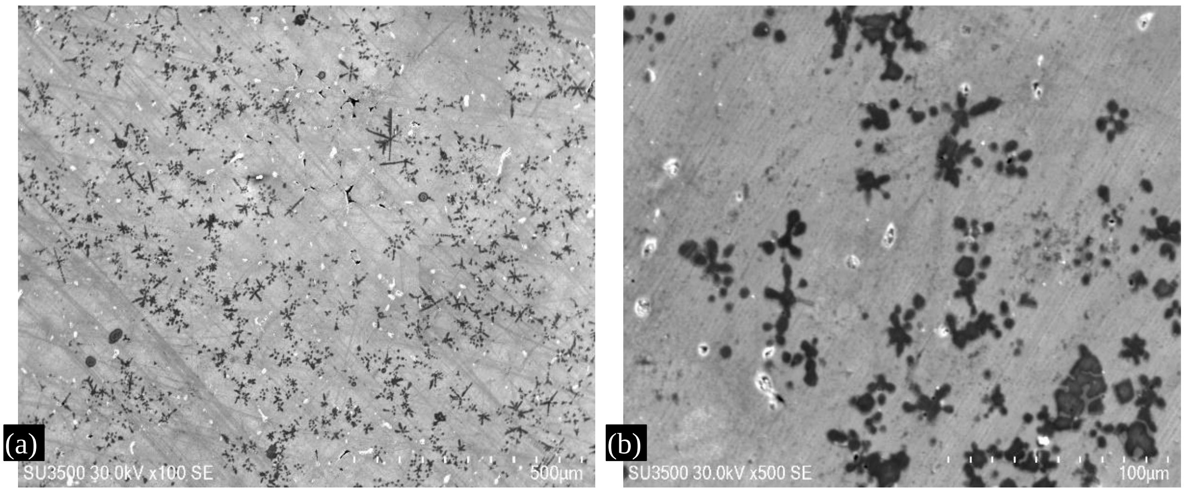

Figure 7. SEM images of Al-Bronze, (a) 100X, (b) 500X.

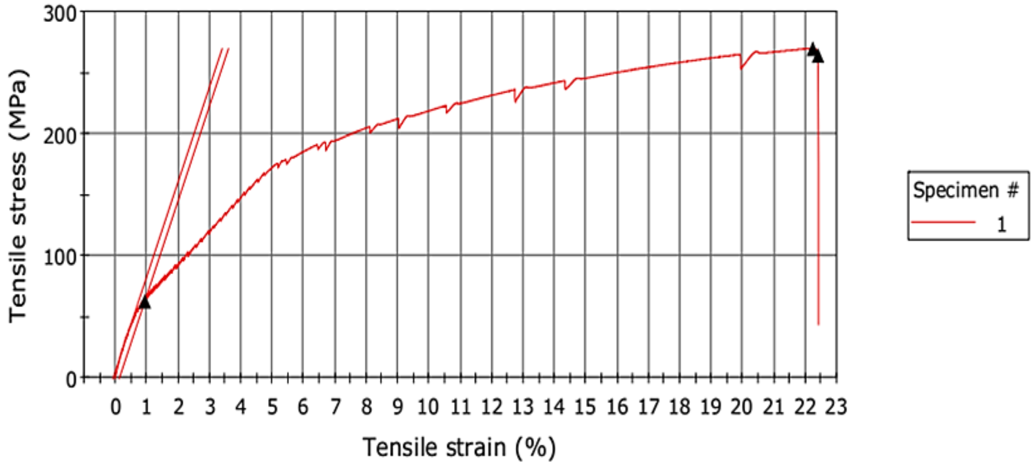

Figure 8. Tensile stress versus tensile strain.

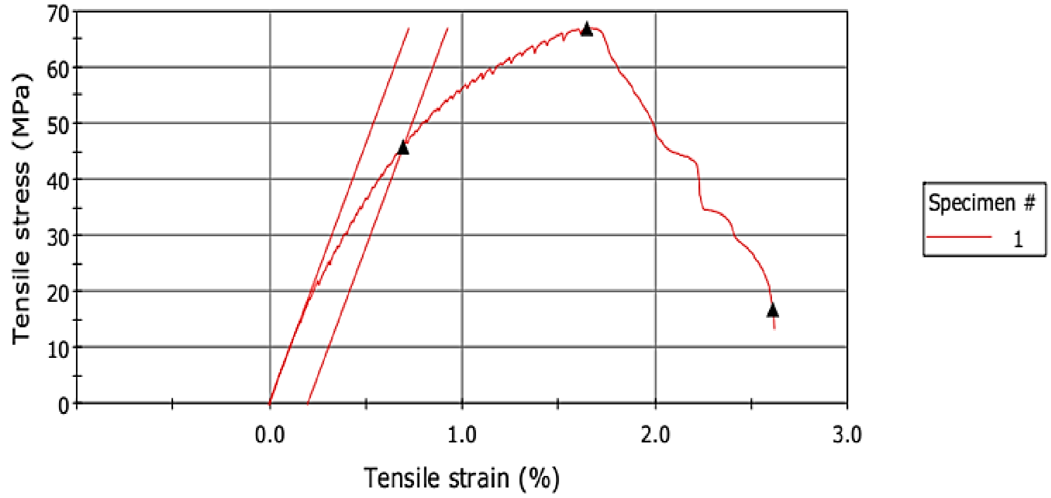

Figure 9. Tensile stress versus tensile strain.

Table 3. The tensile test result of Brass

	Maximum load (kN)	Tensile stress at Maximum Load (MPa)	Tensile strain at Maximum Load (%)	Load at break (kN)	Tensile stress at Yield (Offset 0.2%) (MPa)	Modulus (automatic young's) (MPa)	Tensile strain at break (Standard) (%)	Extension at break (Standard) (mm)
1.	30.52	269.90	22.21	29.87	63.27	7775.600	22.39	8.955

Table 4. Bronze tensile test results**.**

	Maximum load (kN)	Tensile stress at Maximum Load (MPa)	Tensile strain at Maximum Load (%)	Load at break (kN)	Tensile stress at Yield (Offset 0.2%) (MPa)	Modulus (automatic Young's) (MPa)	Tensile strain at break (Std) (%)	Extension at break (Standard) mm)
1.	7.59	67.08	1.65	1.921	63.27	9227.274	2.61	1.043

Wear Testing Results

The experiment was performed on the prepared samples for 30 min at loads of 10N, 20N, and 30N, at a speed of 200 rpm. The setup was linked to a data collection system that calculated the coefficients of friction and the friction forces of various materials. WINDUCOM software provides a graphical representation of the wear rate, friction force, and coefficient of friction (COF). The findings illustrate how the wear rate is related to the load, speed, and time.

Brass

Table 5 shows the wear results of the brass samples at different loads of 10N, 20N, and 30N at a constant time (30 min) and constant speed (200 rpm). The highest wear rate was observed at a 30N load. As the experimental load was increased, the wear rate of the samples also increased.

Bronze

Table 6 shows the wear results of the Al-Bronze samples at different loads of 10N, 20N, and 30N at a constant time (30 min) and constant speed (200 rpm). The highest wear rate was observed at a 30N load.

The wear rate of bronze was lower than that of brass at each experimental load. Hence, Bronze has higher wear resistance than brass.

Table 5. Wear results of Brass

Load(N)	**Wear(micron)**
10	118
20	245
30	363

Table 6. Wear results of Bronze.

Load(N)	**Wear(micron)**
10	76
20	*140*
30	*222*

CONCLUSION

Microstructural analysis of the experimental samples indicated that brass is composed of α-phase crystals dispersed in a β-phase matrix. The beta-phase appeared darker than the alpha-phase did. A higher volume fraction of the beta-phase and smaller alpha crystals (at a constant alpha-phase content) tend to result in longer interphase boundaries, which improves the mechanical properties of the material. Aluminium-Bronze is comprised of alpha-phase crystals and iron-rich kappa-phase precipitates in a beta matrix. The amount of Al in the alloy determines its mechanical characteristics.

Tensile tests conducted on the samples revealed that brass exhibited a higher tensile strength than bronze. Wear testing conducted on the samples demonstrated that aluminium-bronze possesses higher wear resistance properties than brass. The wear rate of the samples increased with the test load.

Acknowledgements

MKP thanks the OPJU for supporting the experiments. In addition, thanks to experts from VSSUT, Burla, for their support in the discussions.

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