Comparative Study of Copper and Aluminium Bronze Alloy Processed Through Die- Casting Route

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Abstract:

Aluminium Bronze (Al-bronze) part of the Copper alloy family. It is a structural, non-heat treatable alloy offering unmatched properties of high strength, hardness and wear resistance. Al-bronze is extensively used in automobiles, aeronautical, marine, and general engineering applications. In this study copper and bronze with 10% aluminium are prepared by die-casting process and the comparative study has been made. The density of copper and Al-bronze was determined using water displacement method (Archimedes Principle). The average density of copper and Al-Bronze are reported as 8.6975±0.0695 g/cc and 7.610±0.0015g/cc respectively. The microstructure analysis of copper and Al-bronze was carried out using the optical metallurgical microscope. The micrograph (surface topography) of copper and Al-bronze was revealed as equiaxed grains and martensitic structure. The average value of micro-Vickers's hardness of copper and Al-bronze are found to be 619.80±27.51MPa and 1374±97.13MPa. Tensile/ compression test was performed at room temperature using the BISS, 25 kN tensile testing machine. The ultimate tensile strength (UTS) of pure copper is 257±28.33MPa and Al-bronze is 550.95±16.6MPa. Similarly, the compression strength was also measured using the same testing machine and the ultimate compression strength (UCS) recorded for pure copper is 324.46±37.5MPa and Al-bronze is 384±21.31MPa. The tribological properties of copper and Al-bronze were investigated using the Pin-on disc wear testing machine for different speeds and different load conditions. The results are encouraging which calls for wider applications and testing.

***Index Terms*: -** Copper, Aluminium Bronze, Optical Metallurgical Microscope, Tensile Test, Compression Test.

1.INTRODUCTION

Aluminium Bronze is an alloy of copper in which the major alloying element is aluminium whose wt.% varies from 8 - 12%. Alloy having less than 8wt.% aluminium is called single-phase alpha alloys whereas alloy having Al wt.% in the range of 8-12% are called binary alloys. Al-10 wt.% Cu alloy has a widespread application in automobiles, chemicals, petrochemicals, and desalination plants: offshore and shipboard equipment and other general engineering applications. Al-bronze can be hardened by heat treatment and have an enhanced corrosion resistance due to the complex naturally formed protective film of aluminium oxide and copper oxide which self-heals. This gives it a good wear, cavitation and anti-galling characteristics [1] Al-bronze square bars were printed via wire-arc additive manufacturing has fine solidification structure. Additive manufacture exhibited superior tensile properties than cast Al-bronze [2] Al-bronze is adversely used in marine components production such as propellers, shafts, pumps, gears etc. Heat treatment at different temperatures between 750 °C and 1000 °C and rapid cooling to room temperature showed that hardness strongly depended on the applied temperatures. [3]. Heat treating is a metalworking processes used to alter the physical, chemical and some properties of a material. Al-bronze alloy having the Al wt.% range of 5 – 11% has good mechanical properties and are widely used in components such as bearings, gears, and worm gears [4,5]. Castings of copper alloy are used in applications that require high corrosion resistance, high electrical conductivity. Al- Bronze have features like high hardness and improved tensile strength along with high corrosion and wear resistance [6]. Aluminium Bronze has properties that are analogous to mild steel. Sami Ajeel et al concluded the dendrites microstructure was changed to equiaxed grains of α-phase that were formed after homogenization [7]. D.V. Kudashov et al conducted experiments related to spray forming and hot extrusion and produced high-aluminium bronze (12–15 wt.% Al) with a fine and homogeneous grain structure and a fine and homogeneous distribution of intermetallic particles [8]. Xiangru Feng et al tested the performance of underwater laser cladded nickel aluminum bronze by applying zinc protective layer and titanium additives and stated that due to the fast heat loss during underwater laser process, the microstructure is homogeneous and stable [9]. Jisun Kim et al conducted Vickers Hardness Test and found the average hardness of type 1 (transverse) was 196.8 HV1, and the average hardness of type 2 (longitudinal) was 218.4 HV1 [10]. Study conducted by Uyime Donatus et al regarding Hardness in Rockwell Hardness apparatus found the values ranging between 46.5-63.7 HRc and concluded this alloy would be suitable for low/medium strength level application [11]. , S.P. Kumaresh Babu et al mechanical properties in Nickel aluminium

Bronze alloy with Nb and Y for aqueous applications According to the result obtained from the tests, the mechanical properties improved by adding the alloys in the NAB with Nb2% and Y-2% and was recommended for use in marine structures[12] .Nwaeju, C. C et al established that Aluminium Bronze doped with nickel increased the tensile strength, ductility, and impact strength and reduces hardness [13]. S. Alama et al concluded the microstructural imperfections have an adverse effect on the tribological performance [14]. I. Boromei, et al experimented Aluminium bronze-steel sliding contact in packaging applications and found the as-cast produced a continuous and adherent oxide layer which was more stable at the higher speeds and loads and increased the wear resistance and reduced friction [15]. Vipin K. Sharma et al Minimum specific wear rate of the Al-bronze was obtained at (3.95 m/s, 62 kPa) values of sliding speed and pressure and the minimum value of the coefficient of friction between Al-bronze and mild steel was obtained at (4.62 m/s, 124 kPa) [16].

2. EXPERIMENTAL

The 2kg pure copper was melted in an electric resistance furnace which has a melt capacity of 1400 ˚C. After heating it up to the melting temperature (1100 ˚C), the melt was poured into a metallic die of the dimensions [length × breadth × height] (100mm × 80mm × 10mm) respectively. The Al-bronze alloy was prepared by adding 10% by wt. of Al to pure copper, using die casting method. The furnace used for the die casting process of copper and Al-bronze is of the make Aspire INC (coil used: - Si-Carbide). Rectangular bars of 100mm × 50mm × 8mm (length × breadth × height) were placed in a graphite crucible and in turn placed inside the furnace. The melt, which was poured into the metallic die attained the shape of the die due to the gravitational force and was kept for solidification under the room temperature. The samples of pure copper and Al-bronze were prepared to study the surface topography using mill cutting method. For the metallographic investigation. First, four grades of emery papers were used whose grit and grain sizes are 600µm,800µm,1000µm and 1200µm. In the second step, these samples were perfectly polished on a velvet cloth at a set speed of 375rpm using the alumina powder solution (size of powder 1-micron) for 15mins and later with water for 10 mins on the double disc variable speed polisher which is of the make METCO (BAINPOL VTD). Finally, all the polished samples were air dried and etched with a solution made up of [25ml Conc. Nitric Acid (HNO_3) + 25ml distilled water (90%)]. This etching was done for a total time of 50secs in an open beaker containing the solution. The microstructural characterization was performed using an optical metallurgical microscope (Olympus BX53M) which has a total magnification range of 50x-1000x and has a 360-deg. rotatable analyzer slider for reflected light. All the pure copper and the Al-bronze samples were surface investigated individually under the magnifications 50x, 100x, 500x and 1000x. Copper and Al-bronze samples were machined down to the dimensions of 10mm×10mm×10mm (Length × Breadth × Height) respectively for the density measurement. Both samples were individually weighed using the density measuring instrument (Buoyancy Method - Archimedes principle) which mainly consists of a weighing pan assembly, a glass beaker, and a sinker. Weights of these samples were first noted in vacuum, and then in water. The recorded values were substituted in the equation [$\rho=(W1/(W1-W2))$] to calculate the individual densities. The surface Vickers hardness of samples was measured using the micro-Vickers hardness tester (WILSON VH-1102) with the loading force of 10N on the top of the surface starting from one end to the other with a 10 mm distance apart using a diamond indenter. The holding time was a total 15secs at each point. The hardness values were recorded using the software accompanied with the instrument and tabulated accordingly. The average value of five random points measured for each layer was determined as the final result. The Mechanical properties were all evaluated at room temperature under uniaxial tensile loading. Samples were prepared by electro discharge wire cutting method from the cast pure copper and Al-bronze as per the ASTM E8 and ASTM E9 standards for the tensile and compression testing. A computer controlled BISS(NANO) 25kN universal testing machine accompanied by a 25mm extensometer (for accurate measurement of displacement) was used to perform tensile test and a combined tensile engineering stress-strain curve was plotted for the tested samples. A total of eight trails were performed, four on cast pure copper and four samples of cast Al-bronze. A series of tribology tests were performed on Al-bronze and pure copper under varying load conditions 20kN, 40kN, & 60kN.

3. RESULTS AND DISCUSSION

3.1 Density

The density of Pure Copper and Aluminium Bronze were measured using Density Measuring Instrument which works on the Archimedes Principle. The recorded values were substituted within the equation [$\rho=(W1/(W1-W2))$] to calculate the individual densities. Density of an alloy is usually close to the value of main constituents present in the alloy. The density of Aluminium is 2.56 g/cc and is only 29% of that of Pure Copper 8.697 g/cc, therefore the Aluminium content has the more significant influence on alloy density. There is also variation in density because of size difference of different atoms. Due to the melting range being small, Al-Bronze solidify in compact form.

3.2 Microstructure

Fig 1 presents the optical microstructure of the cast-Al bronze (alloy) and Fig 2 gives the view of cast pure copper microstructure. Under typical sand cast cooling conditions pure copper exhibits microstructure consisting of primary, secondary and tertiary dendrite and numerous primary dendritic structures as revealed by the micrograph (a). Based on the rate of cooling from melt temperature to room temperature we see the formation of coarse, fine and ultrafine grain structure formation (b). Fine grains and finer structures are formed when the solidification rate is very high. As the distance increases from the surface of the mould, into the interior of the casting, rate of solidification decreases, $\lambda 2\lambda 2$ increases and grain size of the casting increases rendering a poor combination of mechanical properties. Primary axis of the dendrite is due to growth at the edge of the crystal. The projection forms a needle, and then moves towards the direction of heat flow. Further, the secondary and tertiary branches will grow similar to the formation of the stem (Primary Stem). In pure metal dendritic growth is formed by freezing at regular intervals. In alloys the dendritic growth appears by cored structure. Coring is formed by different freezing processes. When the undercooling is not sufficient, cellular growth may still occur. Thus, cellular growth precedes dendritic growth. The cellular structure is produced as a collection of hexagonal rods. The hexagonal rods develop into the liquid and reject solute at the interfaces. After a certain level of undercooling, cellular growth gives way to dendritic growth. Due to this there is preferential development of the select cells. Fig 2 shows with addition of 10 percent aluminium the microstructure exhibits martensitic structure which normally occurs in a temperature range that can be defined precisely for a given steel. The change occurs at a martensite start temperature (Ms). Ms can occur over a wide range, from 500°C to below room temperature, depending on the hardenability of the metal.

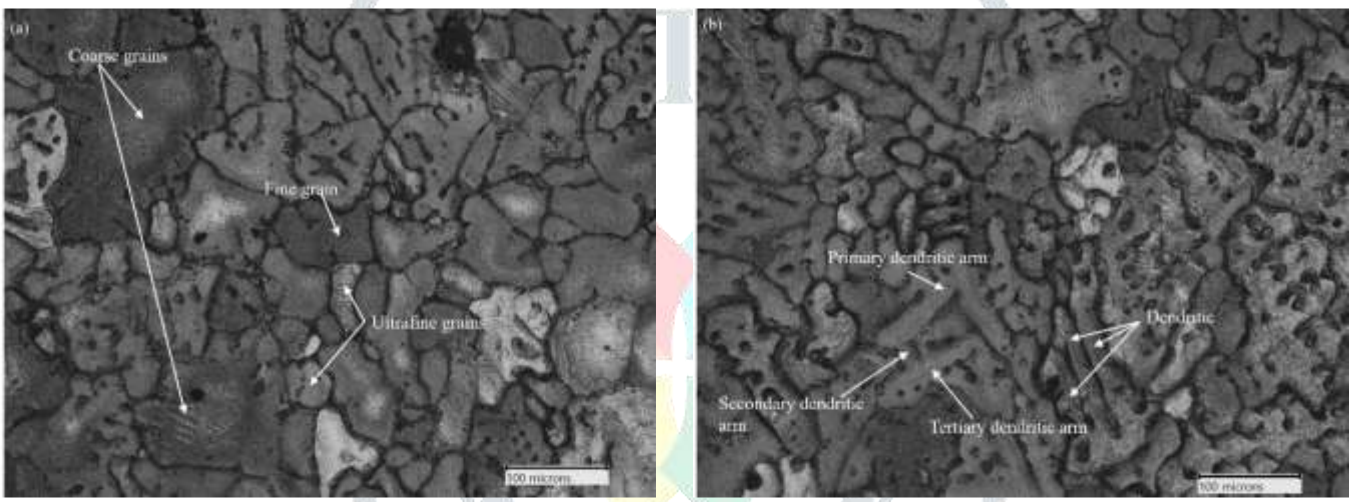

Fig.1 Micrographs of Cast pure Copper (a) and (b) with grain structures.

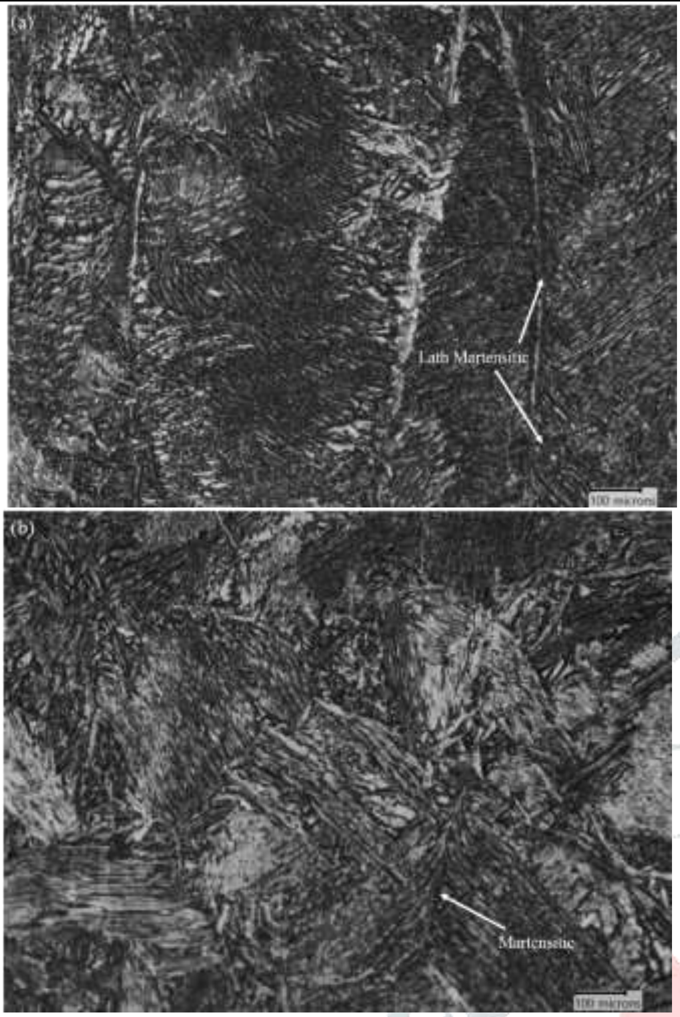

Fig.2 Micrographs of Cast Al-bronze alloy (a) and (b) with its grain structures

3.3 Hardness

The hardness of Pure Copper was found to vary between 60 HV1 to 70 HV1. graph of hardness versus distance of Pure copper is plotted fig 3(a). The maximum hardness obtained was 68.2 HV1, the minimum hardness obtained was 60. 1 HV1 and the mean hardness obtained is 63.2 HV1. Hardness of Pure Copper can be attributed to its Elastic Modulus, Though Aluminium and Copper have the same crystal structure, their bond lengths and bond strengths are very different. Hence their modulus is also different. In ductile materials the crystal structure depends on the dislocation content and their mobility of the atoms. If the dislocations are mobile, they will interact with each other, resulting in high work hardening. Also, if dislocation interactions lead to recovery, the hardness will be lower. The movement of dislocations and its energy are a necessary factor. Copper has a different lattice parameter and SFE (stacking fault energy) than that of Aluminium. Thus, the differences in hardness occur. The hardness of Aluminium Bronze was found to vary between 124 HV1 to 155 HV1 respectively. A graph of the hardness versus distance of Aluminium Bronze is fig 3(b). The maximum hardness obtained was 153.9 HV1, the minimum hardness obtained was 124.6 HV1 and the mean hardness obtained was 140.1 HV1 respectively. On comparing the values of Aluminium Bronze with that of Pure Copper, it observed that the addition of 10% Aluminium by weight has significantly increased the hardness of the metal, also hardness and tensile strength of the metal are directly proportional to each other. More is the hardness of a material more is the tensile strength. As per the results obtained before, tensile strength of Aluminium Bronze is significantly more than that of Pure Copper.

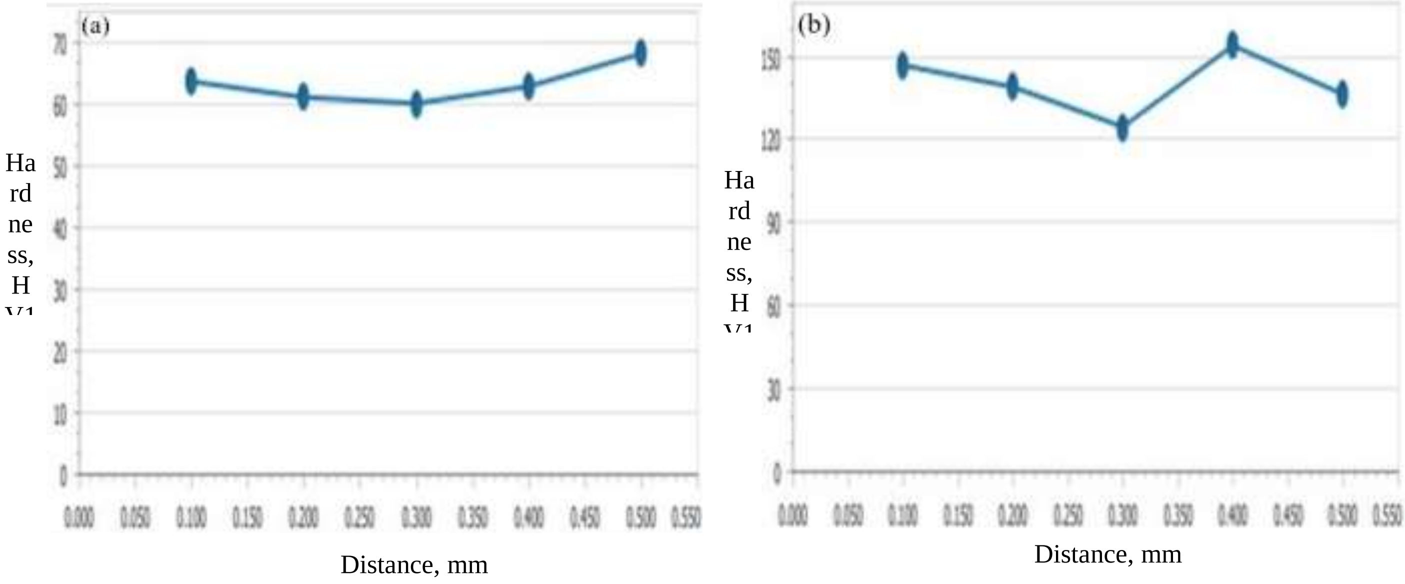

Fig. 3(a) Hardness plot of pure copper (a) and (b) Al-bronze

3.4 Mechanical Properties

The Tensile test was conducted for 4 specimens. In the ranges of strain rate applied, the strain rate influence is nil. All three curves are located in a narrow interval. The differences between them are very small. The shape of the curves is identical as observed for Pure Copper. The curves display a long elastic part at the beginning. Generally, during the first part a steep increase of strength is observed. However, later on, the strength reduces or decreases. In general, it can be observed that Aluminium Bronze have higher mechanical properties that are superior to those of Pure Copper. Compared to commercially available pure copper, the solid-solution alloys have higher tensile strengths and elongations at fracture. It is also can be concluded that addition of 10% Aluminium by weight to Pure Copper has significantly altered the tensile properties of copper. The tensile strength of the alloy also depends on its grain size, this behaviour, occurs because the grain boundaries inhibit slip and contribute to work hardening and the grain-boundary area per unit volume increases as the grain size decreases. Since sample-3 showed extreme values as compared to other three samples, the average of other three samples are taken into consideration.

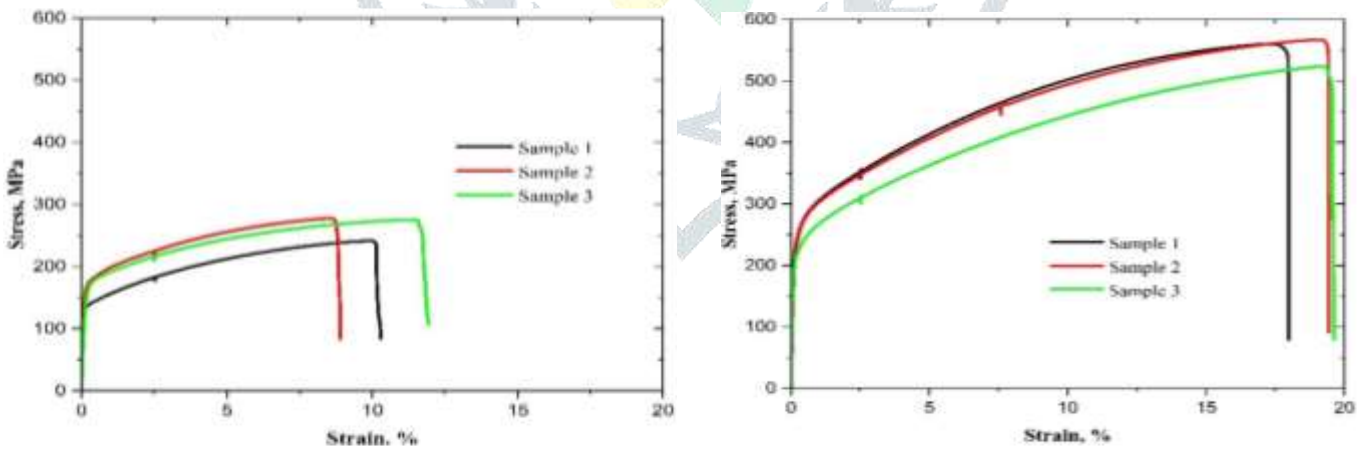

Fig. 4(a) Tensile graph of (a) pure copper and (b) Al-bronze

In the Compression graph as shown below, the maximum compressive stress the specimen can withstand ranges from 260 MPa to 350 MPa respectively. Compressive stress is the force that is responsible for the deformation of the material to an extent such that the volume of the material reduces. It is also known as the stress experienced by a material which leads to a smaller volume. High compressive stress in a material leads to failure of the it due to tension. Since Pure Copper is a ductile material, when the compressive stress is applied to the material that they compress and there is no failure. To some extent, buckling is observed.

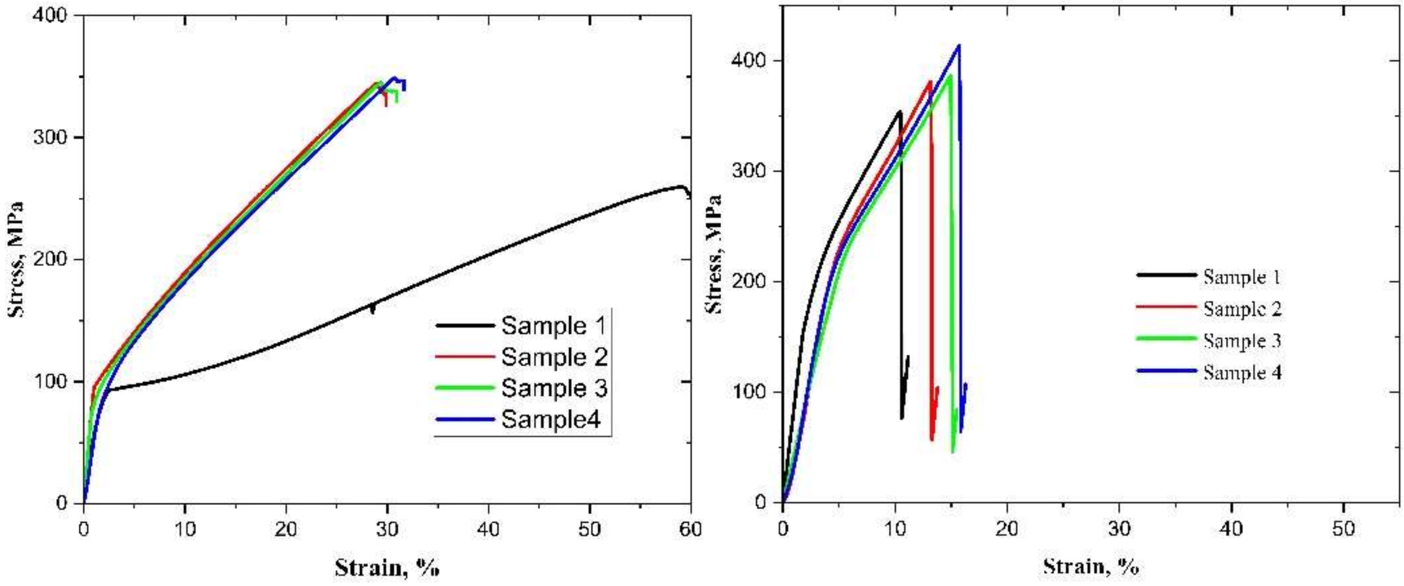

Fig. 5 Compression test Stress Strain diagram (a) Pure copper (b) Al-bronze

The wear test was performed on Aluminium Bronze by for two conditions, they are (i)by keeping the load constant and varying the speed of the disc, (ii) by varying the load and keeping the speed of the disc constant. The conditions were applied for the sample for a time period of 10 minutes. At first, the applied load for the sample was 40N and the speed of the disc is 200 RPM, it can be inferred that there is very less wear of the material. The small variations seen here are the wear taking place due to friction between the surface of the sample and the rotating disc. In the second condition, a load of 40N and disc was set to 400 RPM, the wear was continuous throughout the time period of 10 minutes. The graph linearly varies with respect to time and is almost a straight line. For a load of 40N, with disc speed of 600 RPM, it is seen that there is lot of wear taking place at regular time intervals. The ups and downs in the graph, can be attributed to the sudden wear of the material. This sudden wear is abrasive wear that has occurred. the applied load for the sample was 20N and the speed of the disc is 500 RPM, there is fair amount of wear of occurring throughout the time period of 10 minutes. This wear can be attributed to the increase in the speed of the disc. In the second condition, a load of 40N and disc was set to 500 RPM, abrasive wear was seen repeatedly. In third case, a load of 60N, with disc speed of 500 RPM, wear occurring is significantly more as compared to other two conditions. It can be observed load plays an important role in wear of the material. More the load applied and more the speed of the disc, more is the wear of the sample. But on comparison with Pure Copper, it can be concluded that when Aluminium is added to copper, the resulting wear performance is better than that of Pure Copper. Hence, Aluminium Bronze has more resistance to wear than Pure Copper.

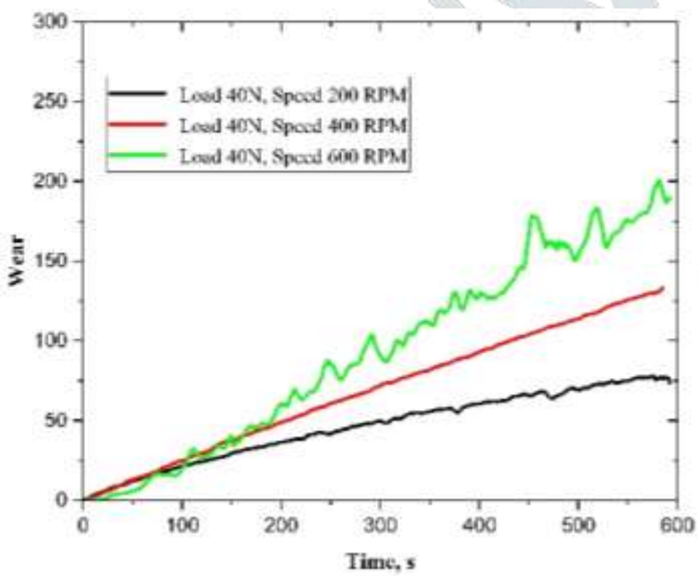

Fig. 5(a) Wear test plot of Al-bronze [variable speed]

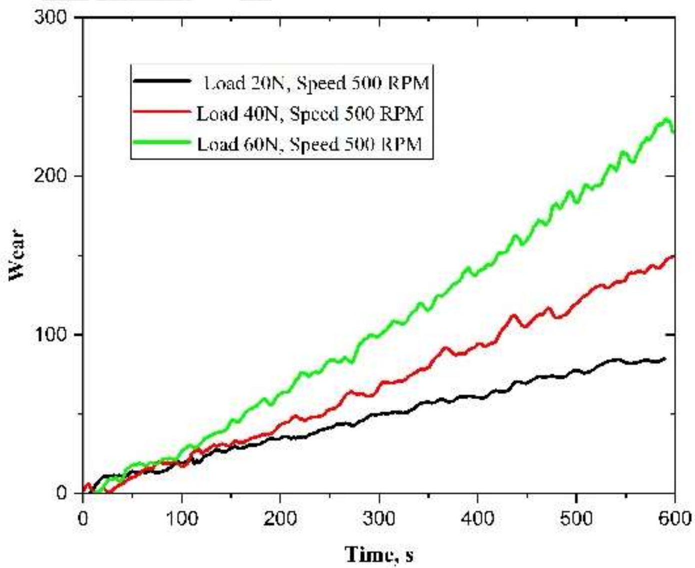

Fig. 5(b) Wear test plot of Al-bronze [variable load]

4. CONCLUSION

Copper and Aluminium Bronze was processed through Die Casting for comparative studies. It was found that the density of Aluminium bronze is less than Copper because of addition of Aluminium to Copper. The microstructure of copper converted from equiaxial to lath martensitic structure after addition of Aluminium, due to increase in nucleation sites. Hardness of Aluminium Bronze increased by twice than that of copper on addition of 10% Aluminium. The Yield Strength of Aluminium Bronze increased from 158.66 MPa to 246.11 MPa. The Ultimate Tensile Strength of Aluminium Bronze increased 2.1 times compared to that of copper. Aluminium Bronze was found to be more wear resistant than Copper when subjected to different condition.

5. SCOPE FOR FUTURE

I. **Fracture analysis** of Al bronze tensile test samples can be carried out.

II. **Under Electron Backscatter Diffraction** (EBSD), **scanning electron microscope** (SEM) can be used to perform the elemental analysis of the cast alloy (10% Al-bronze)

III. Using **X-ray Powder Diffraction,** also known as **XRD,** phases of a crystalline material can be quantified.

REFERENCES

[1] Vipin K Sharma et al, Experimental Study of Tribological Behaviour of Casted Aluminium Bronze, materials today: PROCEEDINGS, Vol 5, 2020, pp 28008-28017

[2] R. Manikandan et al, Investigation of microstructure and mechanical properties in Nickel Aluminium Bronze alloy with Nb and Y for aqueous applications, materials today: PROCEEDINGS, Vol 27, 2020, pp 2591-2595

[3] M. Kaplan et al, The effects of production methods on the microstructures and mechanical properties of an Aluminium bronze, Materials Letters, Vol 57, 2003, pp 4402 – 4411

[4] D.V. Kudashov et al, Spray-formed high-aluminium bronzes, Materials Science and Engineering A, Vol 477, 2008, pp 43–49

[5] R Praveen Kumar et al, Improving the wear and corrosion resistance of nickel aluminium bronze by deep cryogenic treatment, materials today: PROCEEDINGS, 2020

[6] S. Alam et at, Friction and wear characteristics of Aluminium bronze coatings on steel substrates sprayed by a low-pressure plasma technique, Wear, Vol 248, 2001, pp 75–81

[7] I. Boromei et al, Aluminium Bronze- steel sliding contact in packaging applications: Failure analysis and lab scale tribological tests, Engineering Failure Analysis, Vol 112, 2020, 104528

[8] Yuanyuan Li et al, A study of Aluminium bronze adhesion on tools during turning, Journal of Materials Processing Technology, Vol 138, 2003, pp 479–483

[9] W. Chmura et al, bearing composites made from aluminium and aluminium bronze chips, Journal of Materials Processing Technology, Vol 178, 2006, pp 188–193

[10] Chenxi Wang, Estimation of microstructure & corrosion properties of peened Nickel Aluminium Bronze, Surface & coating technology, Vol 313, 2017, pp 136-142

[11] C. Powell, H. Stillman, Corrosion Behaviour of Copper Alloys Used in Marine Aquaculture, International Copper Association, Ltd., New York, 2009, pp. 1–3.

[12] C. Dharmendra, A. Hadadzadeh, B.S. Amirkhiz, G.D.J. Ram, M. Mohammadi, Microstructural evolution and mechanical behaviour of nickel aluminum bronze Cu9Al-4Fe-4Ni-1Mn fabricated through wire-arc additive manufacturing, Additive Manufacturing 30 (2019) 100872.

[13] J. Anantapong, V. Uthaisangsuk, S. Suranuntchai, A. Manonukul, Effect of hot working on microstructure evolution of as-cast nickel aluminum bronze alloy, Mater. Des. 60 (2014) 233–243.

[14] S. Ali, Heat treating of bronzes, Heat Treating of Nonferrous Alloys, ASM Handbook, Vol. 4E ASM International, 2016, pp. 355–396.

[15] R.F. Schmidt, D.G. Schmidt, Selection and application of copper alloy castings, Properties and Selection: Nonferrous Alloys and Special Purpose Materials, ASM Handbook, vol. 2, ASM International, 1990, pp. 346–355

[16] Xiangru Feng, Xiufang Cui, Wei Zheng, Xin Wen, Yao Zhao, Guo Jin∗ , Bingwen Lu, Meiling Dong, Performance of underwater laser cladded nickel aluminum bronze by applying zinc protective layer and titanium additives, Journal of Materials Processing Tech, Vol 266, 2019 pp.544–550

[17] Jisun Kim, Jaewoong Kim and Changmin Pyo, Comparison of Mechanical Properties of Ni-Al-Bronze Alloy Fabricated through Wire Arc Additive Manufacturing with Ni-Al-Bronze Alloy Fabricated through Casting, Metals 2020, Vol 10, pp. 1164

[18] Uyime Donatus, Joseph Ajibade Omotoyinbo, Itopa Monday Momoh, Mechanical Properties and Microstructures of Locally Produced Aluminium-Bronze Alloy, Journal of Minerals and Materials Characterization and Engineering, Vol 11, 2012, pp.1020-1026

[19] S.P. Kumaresh Babu, M. Murali, , A. Vallimanalan, Investigation of microstructure and mechanical properties in Nickel aluminium Bronze alloy with Nb and Y for aqueous applications, materials today: Proceeding, Vol 27, Part 3, 2020, pp. 2591-2595

[20] Nwaeju C. C,Edoziuno F. O and Okoubulu B. A., Structural Modification of Aluminium Bronze (Cu-10%Al) Using Nickel, Delta 2017