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Effect of zinc and nickel micro-additions on the structure and mechanical properties of tin-bronze (Cu-10%Sn) alloy

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Abstract

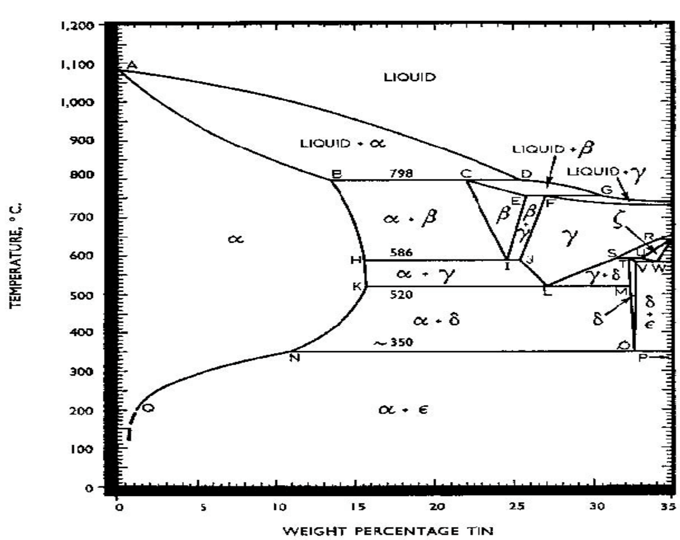
This research work investigated the effect of nickel and zinc micro-addition on the structure and mechanical properties of tin bronze (Cu-10%Sn alloy). The properties studied were tensile strength, percentage elongation using universal tensile machine (130812), impact strength using charpy machine (U1820) and hardness using Brinell hardness tester model B 3000(H). The specimens were prepared by doping 0.2 -1.0wt% of each of the element into Cu-10%Sn alloy at interval of 0.2 percent. The specimens were prepared according to BS 131-240 standard. Microstructural analysis was carried out using optical metallurgical microscope (L2003A) and scanning electron microscope (LEGALMU 11). Result obtained revealed that hardness, impact strength, %elongation and UTS of the alloy increased with increase in concentrations of zinc while only hardness and UTS increased with increase in concentration of nickel. Microstructural analysis revealed the primary α-phase and (α + δ) interdendtritic eutectoid phase and these phases gave rise to the enhanced mechanical properties. Tin bronze doped with nickel and zinc proved to increase mechanical properties and therefore are recommended for applications in engineering and allied industry.

Keywords: microstructure, nickel, zinc, mechanical properties, tin bronze

Introduction

Tin bronze (Cu-Sn) contains copper as the base metal and tin as the major alloying element. The useful range of composition is from 75 to 95% Cu and 5-25% Sn [1]. Tin bronze has good corrosion resistance and strength and are used for applications such as gears and bearings [2]. They are applied extensively for production of hydraulic fittings, pumps linings, utensils, bearings, sheets, rods, wires, etc. This is mainly because of their mechanical properties such as excellent hardness, tensile strength, wear resistance, good corrosion resistance and ductility [1, 2]. Copper-tin binary equilibrium diagram is complex, containing a peritectic reaction and series of eutectoid reactions [3]. From the equilibrium diagram Figure 1, the β-phase would first transform to the α and γ phase, the γ-phase would transform to α and δ and finally the δ would transform to α + ε phase [4]. In practice, the phase generally seen in the microstructures is the α +δ eutectoid phase because δ α + ε reaction occurs extremely slowly and would only take place with prolonged low-temperature heat treatment [4, 5].

Copper-Tin



(***Source*:** Copper Development Association. (1992). Equilibrium Diagrams.CDA Publication No.94, p. 23.)

Fig 1: Cu-Sn phase diagram.

Cast Cu-10%Sn alloy has the basic structure which consists of cored dendrites of α+ (α + δ) eutectoid. The δ ($Cu_{31}Sn_8$)-phase is hard and brittle and therefore decreases the strength and ductility of the alloy [6]. In order to overcome this anomaly, addition of alloying element in micro-quantity is an important technique apart from heat treatments and work-hardening, that is useful for obtaining a suitable structure that will produce the desired mechanical properties in the alloy system [7]. These alloying elements introduce secondary phase particle that interact with dislocation motion thereby producing the desired mechanical properties [8].
Nickel positively affects the mechanical and corrosion properties of alloy. For instance, addition of nickel to copper alloy, improves its strength and durability and also resistance to corrosion and erosion cavitation [9]. Zinc based alloys have a number of advantages over traditional bearing materials [10, 11]. It has been found to be of high strength and cost effective substitute to conventional bearing bronze under heavy load and slow medium speed applications [12, 13]. These advantages can be summarised as high resistance to wear, excellent castability and low cost. Hence, this research work focuses on micro-addition of nickel and zinc to molten Cu-10%Sn alloy in order to improve and modify the structure and mechanical properties of tin bronze.

2. Materials and Methods

2.1 Materials and equipment

The under listed materials and equipment were used for the research work: pure copper scrap (99.9%), tin powder, nickel powder, zinc powder, weighing balance, crucible furnace, venier calliper, bench vice, lathe machine, electric grinding machine, hack-saw, stainless steel crucible pot, mixer, scoping spoon, electric blower, rammer, moulding box, impact testing machine (U1820), hardness testing machine (A 3000 H), universal tensile testing machine (model 130812), emery papers of different grits, air drying machine, metallurgical microscope (L 2003A), digital camera, and VEGA LMU 11 scanning electron microscope machine.

2.2 Method

(a) Melting and casting of alloys

This operation was carried out to produce eleven separate specimens for the research work. The bailout crucible furnace with steel crucible pot was pre-heated for about 10minutes. For the control sample, 563.42g of Cu and 33.33g of Sn granules were measured out. Copper was charged into the furnace pre-set at 1150ºC and heated till it melted. Tin granules were then added to the melt and stirred properly to ensure homogeneity. The alloying elements (nickel and zinc) were then introduced separately into the melt (Cu-10%Sn) based on the compositions, after the control sample had been cast. The melt was manually stirred intermittently in order to ensure homogeneity and facilitate uniform distribution of the alloying element. Sand casting method was used after removal of the molten metal alloy from the furnace and carefully skimming off the dross. The molten metal was poured into the mould cavities and allowed to solidify for about 3minuties before removal from the mould.

(b) Machining

The machining operation was carried out using a three jaw chuck lathe machine. The samples to be machined were firmly clamped on the machine and facing, turning and shaping operations were done on the clamped samples with the aid of a cutting tool mounted on the post of lathe machine. Eventually the required dimensions for impact, tensile and hardness test samples as well as microstructure analysis were obtained, and displayed in figures below.

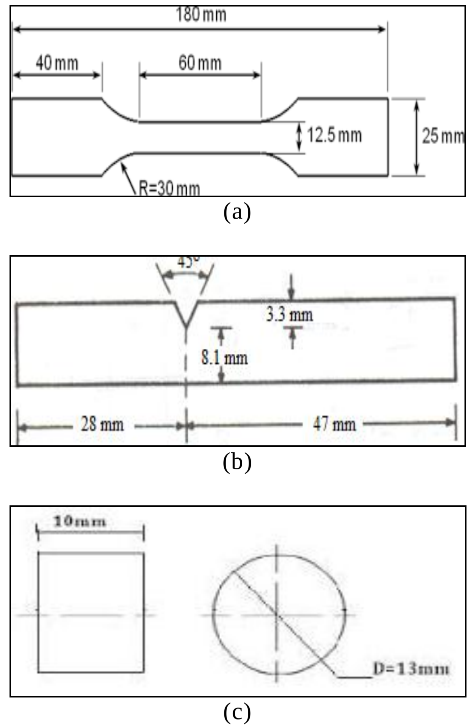


Fig 2: (a) Tensile test specimen **(b)** Notch impact test specimen, **(c)** Hardness/microstructure specimen.

(c) Mechanical Test

The tensile strength was determined with 13081 tensile testing machine, while a Brinell hardness machine with 2.5mm diameter ball indenter and 62.5N minimum was used to determine the hardness. This equation BHN $= \frac{P}{(\frac{\pi D}{2})\ (D-\sqrt{D^2-d^2})}$ was used in calculating the result of the hardness. Where BHN: is the brinell hardness number, P: is applied load (N), D: ball (indenter) diameter (mm), d: notch diameter (mm). Charpy impact test machine (U1820) was used to carry out impact strength.

(d) Microstructure examination

The microstructure of experimental specimens was studied using optical metallurgical microscope and scanning electron microscope linked with EDS analyzer. Preparation of specimens was done by grinding, polishing and etching, so that the structure can be examined using optical metallurgical microscope. The samples were ground by the use of series of emery papers in order of 220, 340, 400, 600, 800, 1000, and 1200 grits and polished using fine α-alumina powder. An iron (iii) chloride was used as the etching reagent before mounting on the microscope for microstructural examination and photographing. For SEM observation, materials were etched with hydrogen fluoride (HF). Chemical composition of materials was made by EDS (EDS analyzer Brucker Quantax) attached to the SEM using the Software thermo noran.

3. Results and Discussion

Results of ultimate tensile strength (UTS), impact strength, ductility (% elongation) and hardness responses by test specimens are displayed in Table 1 and Figures 6-9 while the microstructures developed by the specimens are shown in Plates 1- 14 with the corresponding EDS analysis shown in Figure 3-6. Apart from different intermetallic phases, two major phases were revealed under the optical metallurgical microscope viz: α-phase and the (α + δ) eutectoid, in proportions determined by nickel and zinc contents and mould materials during casting. The alloy contents influenced the grain size and the nature of α-phase (copper-tin solid solution), - extent of coring as well as the amount of (α + δ) inter-dendtritic eutectoid as shown in Plate 1. The mechanical properties of Cu-10%Sn alloy are crucially influenced by their microstructural features. The δ-phase is an intermetallic compound of $Cu_{13}Sn_8$. Increase in the amount of δ-phase in the microstructure will make the alloy hard and brittle which therefore decreases strength and %elongation of tin bronze.

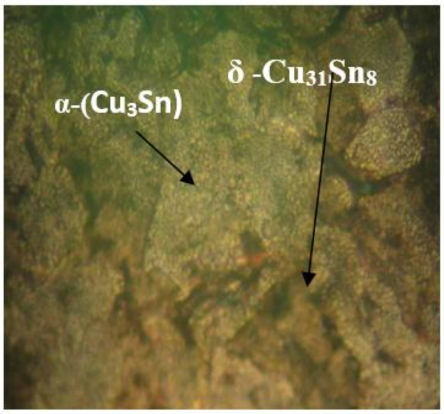


Plate 1: Cu-10%Sn alloy (Control)

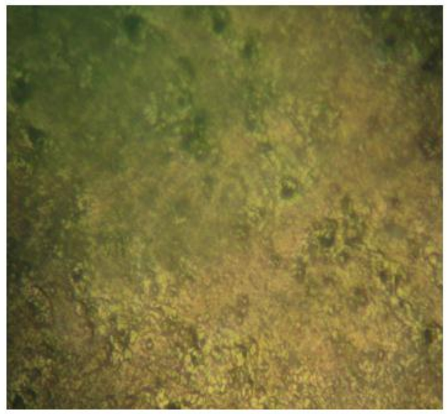


Plate 2: Cu-10%Sn + 0.2% Ni

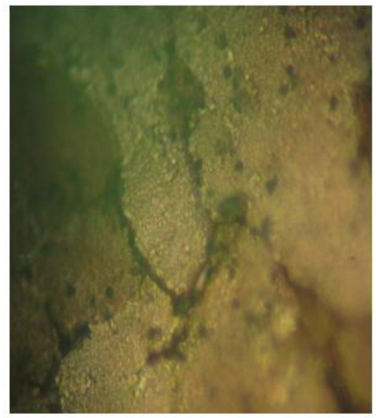


Plate 3: Cu-10%Sn + 0.4% Ni

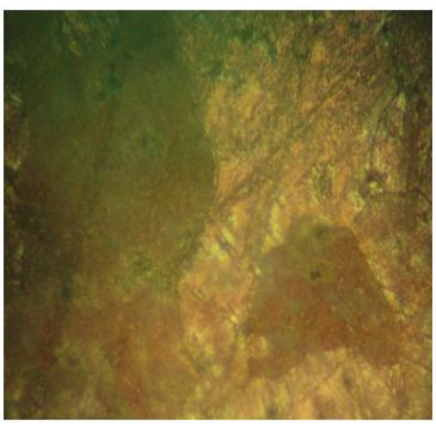


Plate 4: Cu-10%10Sn + 0.6% Ni

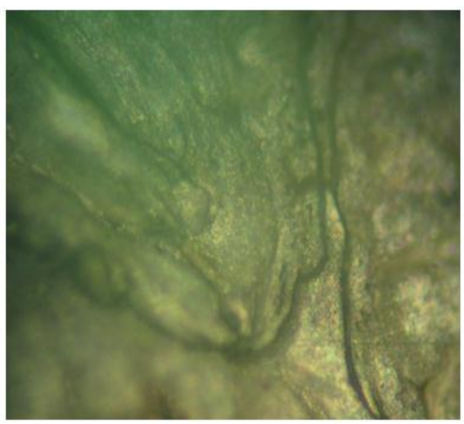


Plate 5: Cu-10% + 0.8% Ni

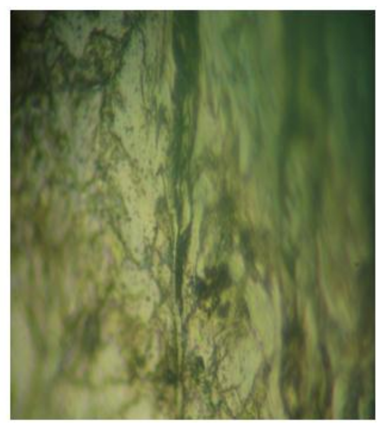


Plate 6: Cu-10%+ 1% Ni

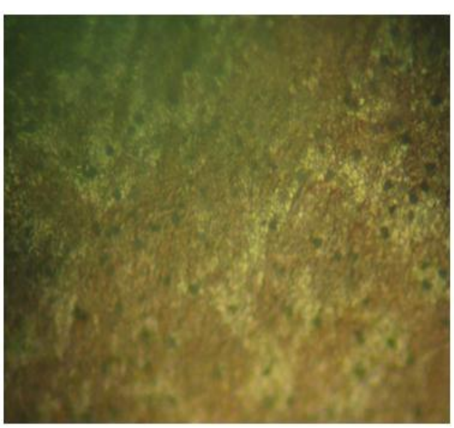


Plate 7: Cu-10%Sn + 0.2% Zn

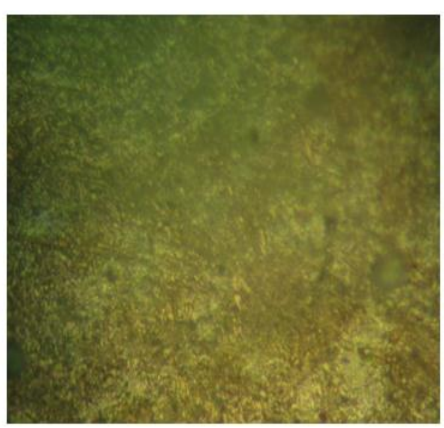


Plate 8: Cu-10Sn% + 0.4% Zn

Plate 9: Cu-10% + 0.6% Zn

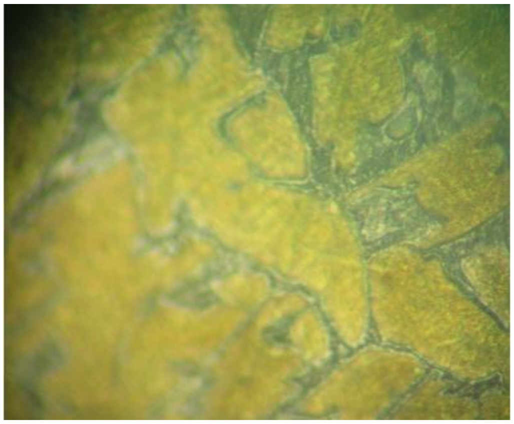


Plate 10: Cu-10% + 0.8% Zn

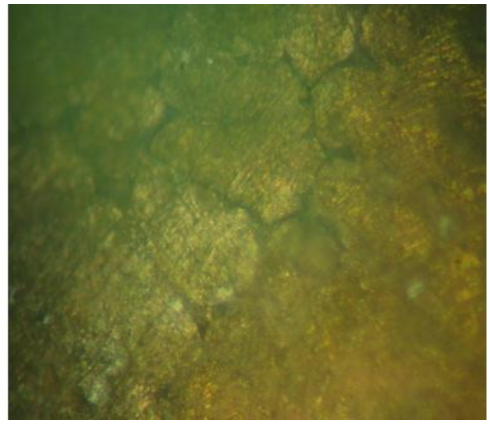


Plate 11: Cu-10% + 1% Zn

Plates 12, 13 and 14, shows the scanning electron micrographs of Cu-10%Sn alloy doped with 0wt%t, and 1wt%Ni, and 1wt%Zn with corresponding EDS analysis indicated in Figure 3-5. The micrographs show that there was gradual increase in intermetallic compound from the grain boundaries as the concentration of zinc and nickel increased. From Plate 14, it could be seen that the spread of intermetallic compounds ($\alpha + \delta$) was limited, which further explained how an increase in zinc concentrations improved the ultimate tensile strength, impact strength, hardness and ductility.

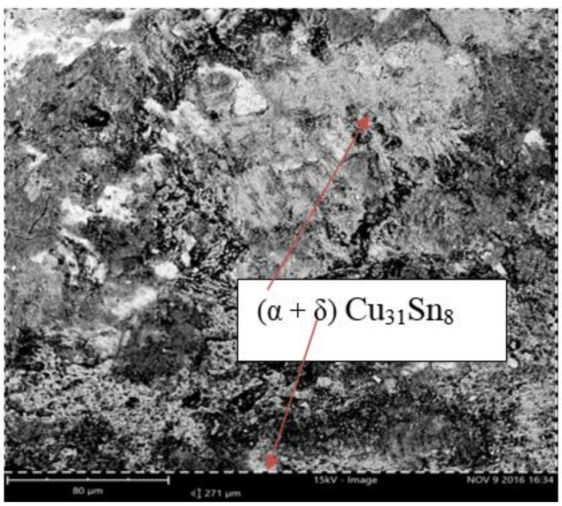


Plate 12: SEM micrograph of Cu-10%Sn alloy (Control)

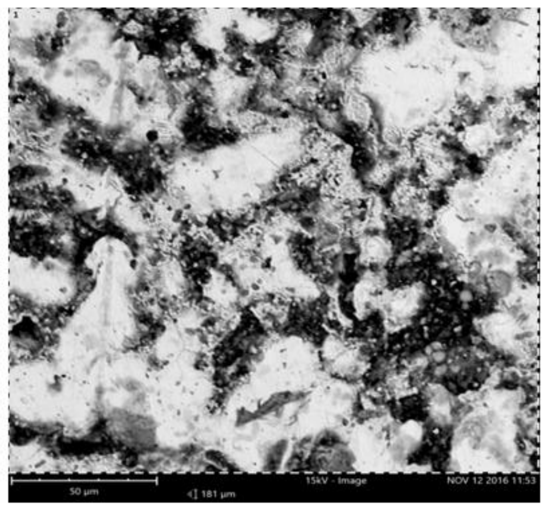


Plate 13: SEM micrograph of Cu-10%Sn + 1%Ni

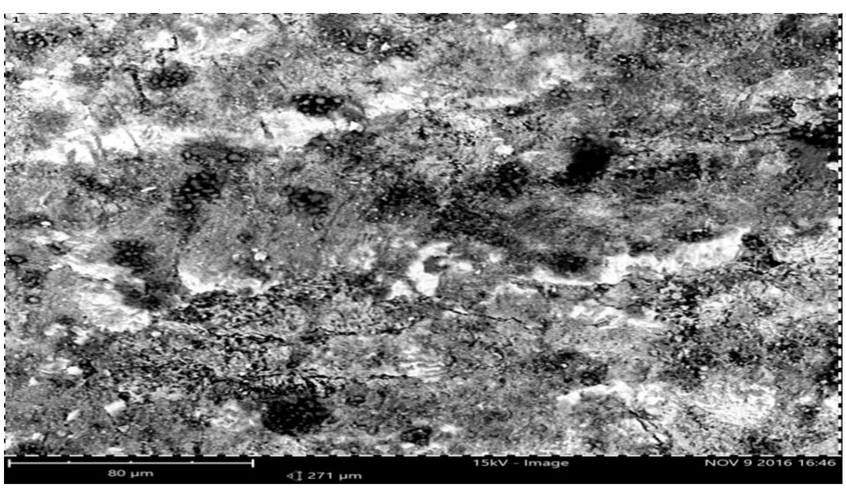


Plate 14: SEM micrograph of Cu-10%Sn +1%Zn alloy

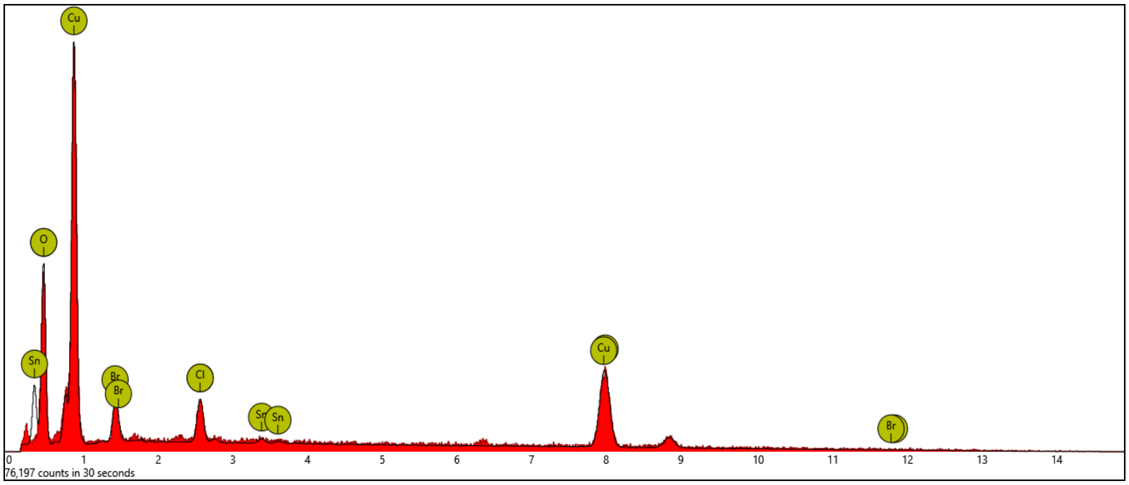


Fig 3: EDS spectrum of Cu-10%Sn alloy

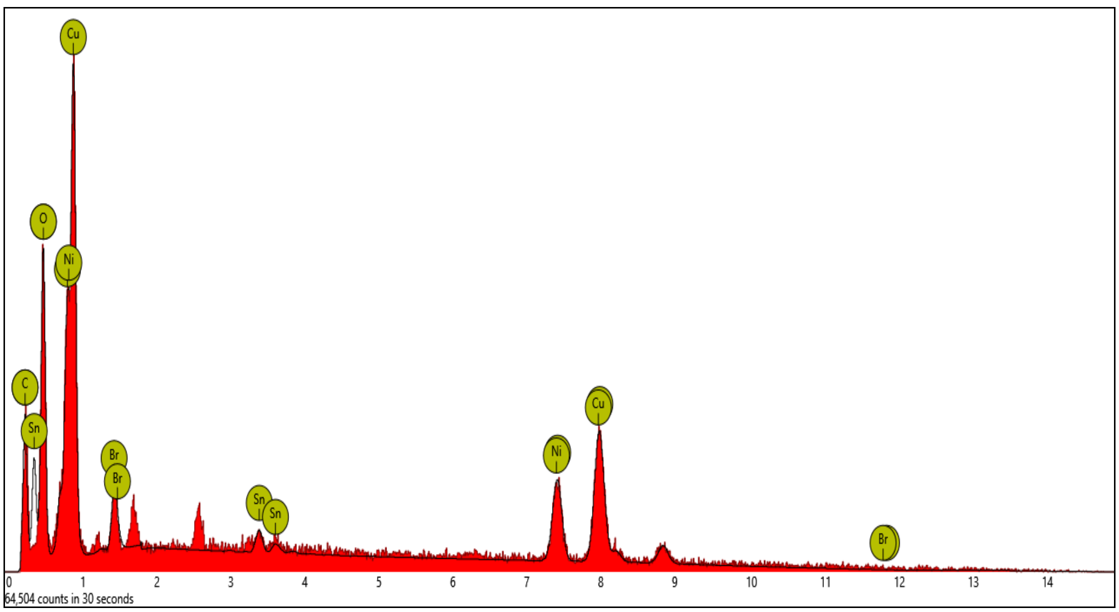


Fig 4: EDS spectrum of Cu-10%Sn-1%Ni alloy

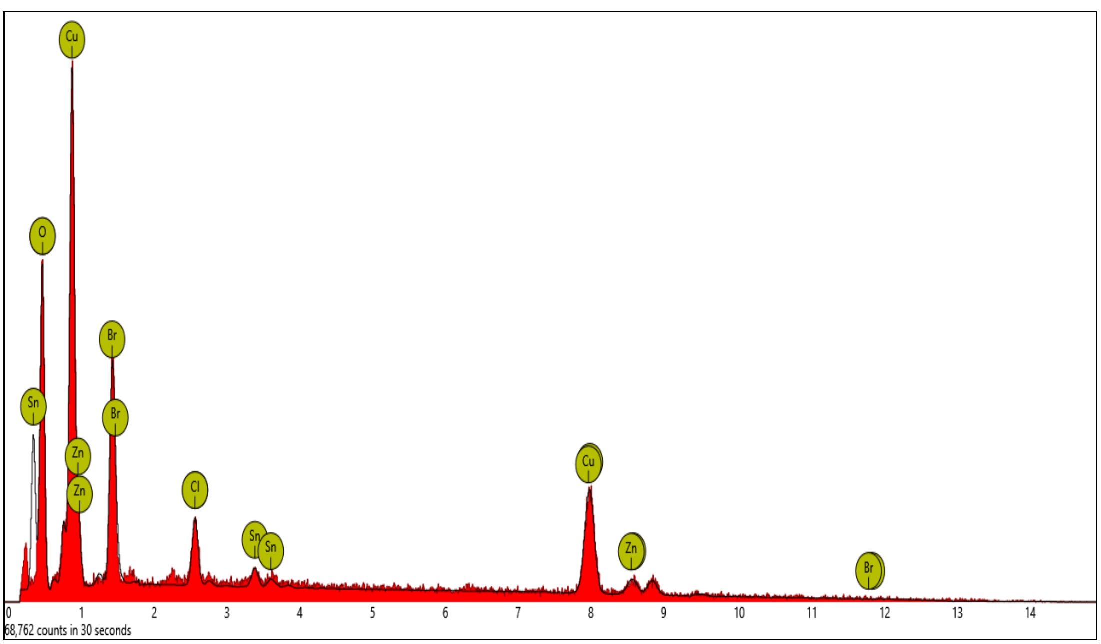


Fig 5: EDS spectrum of Cu-10%Sn-1%Zn alloy

Table 1: Mechanical properties of Cu-10%Sn doped with nickel and zinc

Alloy composition	UTS (MPa)	% Elongation	Hardness (BHN)	Impact (Joules)
A (Cu- 10%Sn)	149	15.0	135	12
A + 0.2% Ni	241	16.0	219	29
A + 0.4%NI	255	15.4	231	26
A + 0.6% Ni	276	14.1	245	21
A + 0.8% Ni	297	11.5	256	14
A + 1% Ni	300	10.0	275	9
A + 0.2% ZN	253	15.3	235	27
A + 0.4%Zn	276	16.5	240	31
A + 0.6% Zn	285	16.7	253	32
A + 0.8% Zn	306	17.1	283	39
A + 1% Zn	310	17.3	213	63

The variation of tensile strength, hardness, %elongation, and impact energy of the test alloys as a function of nickel and zinc content are shown in Table 1 and Figure 6-9. From figure 6, it was observed that micro-addition of all the elements within the studied range of composition improved ultimate tensile strength as compared to the control sample (Cu-10%Sn). It was equally noted that zinc with 1wt% had the highest value of UTS among the dopants.

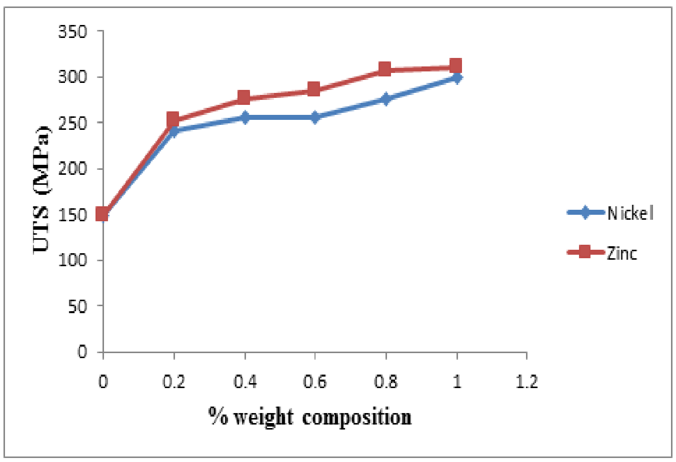


Fig 6: Effect of alloy compositions on the UTS of tin bronze (Cu-10%Sn)

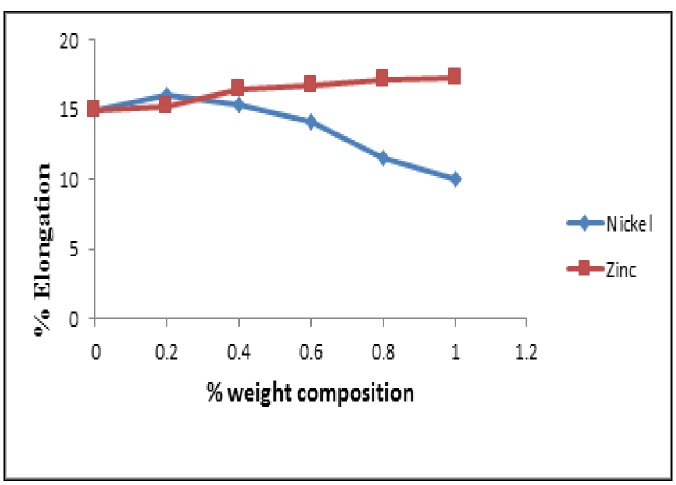


Fig 7: Effect of alloy compositions on the % elongation of tin bronze (Cu-10%Sn)

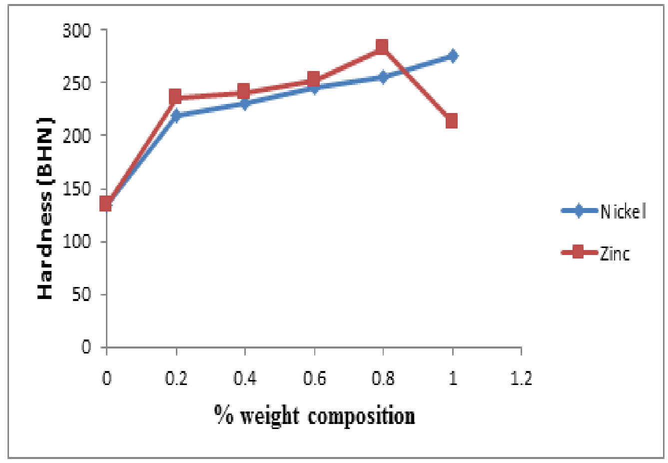


Fig 8: Effect of alloy compositions on the hardness of tin bronze (Cu-10%Sn)

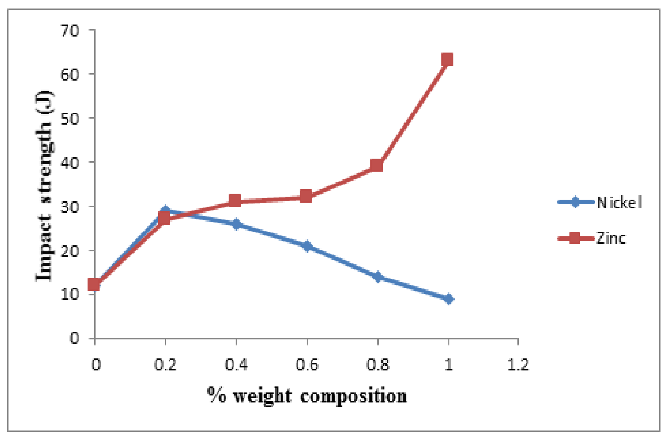


Fig 9: Effect of alloy compositions on the impact strength of tin bronze (Cu-10%Sn)

Figure 7 and 9 shows the effect of dopants on the % elongation and impact strength of Cu-10%Sn alloy. It was observed that steady decrease in % elongation and impact strength was obtained when nickel was doped with Cu-10%Sn alloy. Nickel recorded high value of impact strength and ductility at 0.2wt%. The decrease observed in the properties was as result of over clustering of particles which is shown in Plate 4, 5, and 6. When nickel content increased, formation of hard and brittle δ-(Cu_{31}-Sn_8) eutectoid predominate, this weaken the interdendritic region of the alloy matrix and thus, cause crack initiation and subsequent failure. Impact strength and ductility improved by addition of zinc to Cu-10%Sn alloy. The value of the properties increased with increase in concentration of zinc element. In Figure 8, the hardness values increased with increase in composition of dopants in the alloy matrix. Maximum hardness value of 283BHN was obtained when Cu-10%Sn alloy was doped with zinc at 0.8wt%. The types of microstructure developed in the alloy significantly influence the hardness responses of the corresponding compositional weight percent of the alloy element in the alloy matrix.

4. Conclusions and Recommendation

This research work has shown that addition of micro-additives to tin bronze enhanced improvement of the mechanical properties. In summary, the results of this study have shown that tin bronze had an improved mechanical properties and structure when doped with zinc. The high value of UTS, ductility, impact strength, reduces the cause of failure in engineering designs and constructions.

- Nickel, greatly improved UTS and hardness but show reduction in impact strength and ductility.
- Tin bronze alloyed with zinc and nickel is one of the best anti-frictional materials because of the excellent properties shown in this study and this makes it to be suitably used as a ball-bearing alloy (Mao, et al 2007).
- Tin bronze alloyed with zinc is therefore recommendable for use in making gears, bearings, pumps, rods, sheets, etc. as against tin bronze alloyed with nickel.

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