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Effect of vanadium and chromium macro-additions on the structure and mechanical properties of aluminium bronze (Cu-10%Al) alloy

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Abstract

This research work investigated the effect of vanadium and chromium macro-additions on the structure and mechanical properties of aluminium bronze (Cu-10%Al alloy). The properties studied were tensile strength, yield strength, percentage elongation using universal tensile testing machine (SRNO0723), impact strength using charpy machine (U1820) and hardness using Brinell hardness tester model B 3000(H). The tests were conducted according to BS 131-240 standards. The specimens were prepared by doping 1.0 -10wt% of each of the element into Cu-10%Al alloy at 1.0 percent interval. Microstructural analysis was conducted using L2003A reflected light metallurgical microscope. Results obtained showed that hardness, impact strength, %elongation and UTS of aluminium bronze increased with increase in concentration of chromium while only UTS, impact strength and hardness increased with increase in the concentration of vanadium from 1-6wt%. Microstructural analysis revealed the primary α-phase, β-phase (α +γ_2 intermetallic phase) and fine stable reinforcing kappa phase and these phases resulted to the enhanced mechanical properties. Aluminium bronze doped with vanadium and chromium proved to increase mechanical properties and therefore is recommended for applications in engineering industry for the production of offshore and shipboard plant, marine propeller, iron and steel making.

Keywords: microstructure, aluminium bronze, vanadium, chromium, mechanical properties

Introduction

Aluminium bronze are copper based alloys with aluminium as the major alloying element usually in the range of 2-14% in the alloy [1]. Other alloying elements such as iron, nickel, manganese, tin and silicon are also added to aluminium bronze depending on the intended applications [1]. Aluminium bronze is useful in a great number of engineering structures with variety of the alloy finding their applications in different industries. They are available in both cast and wrought forms and these offer them good combination of mechanical properties and corrosion resistance [1, 2, 3]. It can be classified in two kinds; the binary aluminium bronze and multi-component aluminium bronze [4, 5].

Cu-Al alloys offer a combination of chemo-mechanical properties, unmatched by other series which show low rates oxidation resistance at high temperatures and excellent resistance to sulphuric acid, sulphur dioxide and other combustion products. Hence, they are used for applications where their resistance to corrosion makes them preferable to other engineering materials [6, 9]. These features often make aluminium bronze the first choice and sometimes the only logical choice for demanding applications [9, 10]. Aluminium bronzes are finding increasing used in chemical, petrochemical and desalination plants, marine, offshore and shipboard plant, power generation, aircraft, automotive and railway engineering, iron and steel making, electrical manufacturing and building industries. Foundry products achievable from the alloy are propellers, shafts, pumps and valves, water cooled compressor, non-sparking tools [7, 8]. In spite of these wonderful attributes posed by aluminium bronze, aluminium bronze have problem of self-annealing and embrittlement when slowly cooled at normal cooling rate. They exhibit deficient response in certain critical applications such as sub-sea weapons ejection system, aircraft landing gears component and power plant facilities. The need to overcome these obvious performance limitations is imperative to meet today’s emerging technology’s needs. Structural modification in aluminium bronze is accomplished through any or combination of the following processes; heat treatment, alloying and deformation. The choice of method however is usually determined by cost and effectiveness.

The mechanical properties of aluminium bronze apart from aluminium depend on the extent to which other alloying elements modify the structure. In this regard, this research aims at modifying the structure of Cu-10%Al alloy, by the additions of vanadium and chromium at macro level to impact on the types, forms and distribution of phases within the matrix and their effects on the mechanical properties.

Vanadium is a very strong ferrite stabilizer with high solubility in pure iron [11]. It forms carbide and nitride at low temperature, promotes ferrite in the microstructure and increase toughness [12]. According to Muroga (2005), vanadium based alloys are attractive structural materials for breeding blanket of fusion reactors because of their low activation properties and high temperature strength

[13]. Its addition to bronze is very effective in reducing β-grain size.

Chromium is also one of the most important alloying elements [12]. It increases the resistance to oxidation at high temperature and promotes ferritic microstructure. As a strong carbide formers, its carbide increases edge – holding property and wear resistance. It improves cutting performance due to formation of wear resistant carbides, and improvement of the tempering resistant [14, 15].

2. Materials and Method

2.1 Materials and equipment

The under listed materials and equipment were used for this research work; pure copper scrap (99.9%), pure aluminium scrap, chromium powder, vanadium powder, weighing balance, crucible furnace, venier calliper, bench vice, lath 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 SRNO0723), emery papers of different grits, air drying machine, metallurgical bench microscope (L 2003A) with digital camera.

2.2 Method

The methodology adopted to carry out these research essentially involved alloy preparation by melting and casting techniques. The alloying elements (vanadium and chromium) were added separately in concentration of 1 - 10% by weight to molten Cu-10%Al alloy, stirred and sand cast. Subsequently, specimens obtained from the casting were subjected to machining and mechanical test such as ultimate tensile strength, impact strength, yield strength, hardness and ductility. The microstructure of the samples was also studied using, metallurgical microscope.

2.2.1 Experimental procedure

a) Mould preparations

Sand mould was prepared and used for the casting of the specimens. Impurities such as metals, hard lumps, stones etc. were removed from the sand using sieves 500µm and 400µm to obtained fine grain size. The sand was mixed well to ensure uniform distribution of the ingredients. The foundry floor was cleared of dirty and floor board was put in place. Some moulding sands were sprinkled on the floorboard surface and then patterns were introduced. Moulding sand was introduced and rammed. The patterns were carefully withdrawn and the cavities created were repaired. After the pattern was removed and mould repaired, ash was then sprinkled to the cavities to enhance easy flow of the molten metal inside.

b) Melting and Casting of alloys

This operation was carried out to produce twenty one separate specimens for the mechanical and microstructural analysis. The bailout crucible furnace with steel crucible pot was pre-heated for about 10minutes. For the control sample, 163.44g of Cu and 17.18g of Al were weighed out. Copper was charged into the furnace pre-set at 1100°C and heated till it melted. Aluminium was then allowed to dissolve in the molten copper for 6minutes and stirred properly to ensure homogeneity. The alloying elements (vanadium and chromium) were then introduced separately into the melt (Cu-10%Al) based on the compositions, after the control sample had been cast. The melt was manually stirred intermittently in order to ensure homogeneity and facilitate uniformity in the distribution of alloying element. Then molten metal was poured into the mould cavities and allowed to solidify for about 3minutes before removal from the mould.

c) 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.

d) Tensile test

The tensile test was conducted using horizontal bench top Mansanto Tensometer machine (SRNO0723) at room temperature. Specimens for this test were machined to a dumbbell shape which is the required standard specifications so as to fit the grips as shown in Figure 2.1. The testing process started with the specimen labelled 1 and continued on to 21. The specimens were placed each between the two grips, these held the specimen in place, gradually force is applied on the work piece till it fractured. Different values of force and extension were obtained and recorded. Hence, the specimen were tested to determined their ultimate tensile strength, ductility (%elongation) and yield strength. These properties determined were tabulated in Table 2.1.

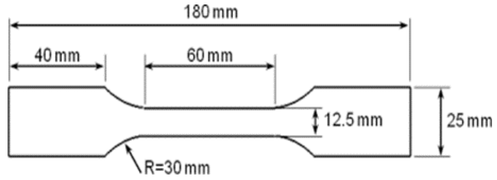

Fig. 2.1 Tensile test specimens

e) Hardness Test

This test was conducted using a Brinell testing machine model B3000 (H). The specimen each 20mm in diameter were polished, placed on an adjusting table below the control panel separately, the table was raised to the focus of the microscope which helped to determine the exact spot for indentation. On pushing the start button on, the microscope returned automatically to its resting position and the spherical indenter was carefully placed on the specimen surface. A specified force was applied and maintained for about 15seconds after which the indenter bounced back to its formal position. The indentation was clearly seen on the monitor of the Brinell testing machine, the diameter of the indentation was obtained by placing four metric lines on the edges of the indentation using hand control knob. The diameter obtained and the force applied was used by the machine to calculate the Brinell hardness of the work piece. Brinell hardness result was displayed on the bottom left hand corner of the monitor. Three (3) indentations were taken on each specimen and the mean was obtained.

f) Impact test

Impact test was carried out with charpy impact test machine model (U1820). The specimens were machined to a dimension of (10 x 10 x 55) mm with a V-notch of depth 2.5mm at its mid-point. The samples to be tested were placed at the machine's sample post with the notch facing the hammer. The hammer was raised to an angle of 45^{o}C and released to swing through the positioned sample in order to break it. As the sample was broken by the swing hammer, the impact energy absorbed was read from the charpy impact energy scale calibrated in joules. Hence, the impact energy of all the samples as well as the control sample was captured.

g) Microstructural examination

The microstructure of the experimental specimen was studied using optical metallurgical microscope. In the process, a cubic sample was cut from each of the 21 cast samples. The samples were ground by the use of series of emery papers of different grits with decreasing coarseness from 220, 340, 400, 600, 800, 1000 and 1200 grades and polished using fine α-alumina powder. The specimens were washed thoroughly and dried using the oven dryer. After drying, the specimen were inserted into dilute hydrofluoric acid which was the etching reagent for about 10-15 seconds and layers of the specimens were attacked chemically until the polished surface were slightly discoloured or dull in appearance. The etched specimens were washed in water to stop the etching action. The specimens were dried and viewed under a high power electron microscope with a magnification of x400 for microstructure analysis and micrographs showing the different morphologies of the cast alloy were taken.

3. Results and Discussion

Results of ultimate tensile strength (UTS), impact strength, ductility (% elongation) and hardness responses by the test specimens are displayed in Table 1 and Figures I-4 while the microstructures developed by the specimens are shown in plates 1-21. From Table 1 and Figure 1, it could be observed that macro-addition of all the elements within the studied range of composition improved ultimate tensile strength as compared to the control sample (Cu-10%Al). It can further be seen that the rate of increase varied with increase in concentration of the alloying elements. For vanadium, the tensile strength increased up to 6% and decreased steadily. The highest ultimate tensile strength of 707MPa at 6% was observed in this case. Steady increase in UTS of Cu-10%Al alloy was observed as the composition of chromium increased from 1-10%. Highest ultimate tensile strength value of 840MPa in this regard was recorded when 10wt% chromium was added to Cu-10%Al alloy.

Figure 2 shows the ductility response with respect to its linear elongation under deformation. It was observed that percentage elongation of Cu-10%Al which is the control sample was higher than that doped with vanadium. The percentage was seen to decrease up to 6wt% and increased steadily. The trend is an indication that ductility is strongly influenced by the amount of vanadium present during casting. The %elongation of Cu-10%Al alloy increased as the composition of chromium increased. When percentage composition of chromium increased, the α-phase present in the microstructure increased. This led to formation of fine kappa-phase. β -phase decreased both in size and quantity thereby allowing little or no gamma 2 (γ_2) phase to form. The presence of soft kappa-phase in the structure (Plate 18, 19, 20, and 21 of micrographs) suppressed the formation of γ_2-phase within the matrix and promote the transition of copper matrix from brittle to ductile on addition of chromium.

Table 1: Mechanical properties of Cu-10%Al doped with vanadium and chromium

Sample Type	UTS (MPa)	Yield Strength (MPa)	% Elongation	Hardness	Impact strength (joules)
A (Cu-10%Al)	144	98	9.30	103	15.1
A + 1% V	239	190	7.60	105	21.0
A + 2% V	305	200	7.20	114	21.5
A + 3% V	429	294	7.00	118	22.0
A + 4% V	562	378	6.70	122	23.2
A + 5% V	684	394	6.20	120	23.5
A + 6% V	707	426	6.00	115	24.5
A + 7% V	567	350	6.70	110	25.0
A + 8% V	433	267	6.90	106	26.0
A + 9% V	388	225	7.10	99	26.3
A + 10% V	258	201	7.40	103	27.0
A + 1% Cr	467	223	8.83	98	24.4
A + 2% Cr	498	254	8.90	100	26.0
A + 3% Cr	528	276	10.35	105	31.0
A + 4% Cr	605	294	11.64	108	33.5
A + 5% Cr	634	316	11.80	112	33.4
A + 6% Cr	666	346	12.30	116	35.2
A + 7% Cr	701	373	12.71	118	36.0
A + 8% Cr	755	392	14.30	122	36.0
A + 9% Cr	822	416	14.90	128	37.0
A + 10% Cr	840	426	15.10	134	39.1

In Figure 3, hardness value increased as the composition of chromium and vanadium increased. A visible variation was observed in vanadium where the hardness value decreased with increase in composition from 6-10wt%. The control sample (Cu-10%Al) recorded the least hardness value of 103BHN. This is as a result of absence of alloying elements. The absence of other alloying elements beside aluminium paves way for precipitation of $\alpha + \gamma_2$ phase within the copper matrix as seen in Plate 1.

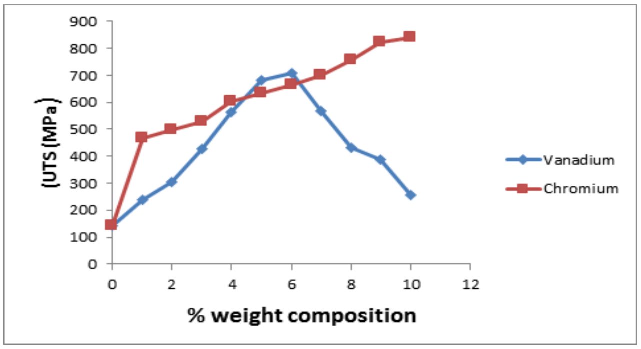

Fig. 1: Effect of alloy compositions on the UTS of aluminium bronze (Cu-10%Al)

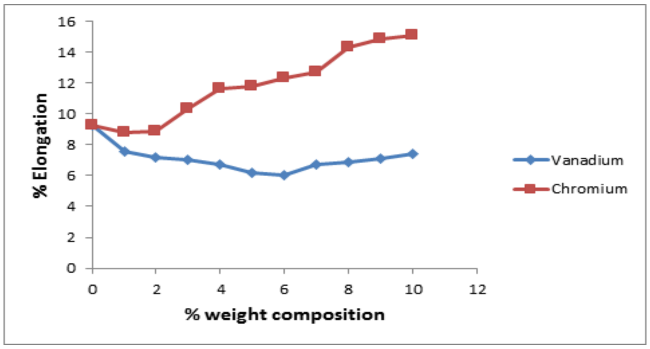

Fig. 2: Effect of alloy compositions on the % elongation of aluminium bronze (Cu-10%Al)

The linear changes on mechanical properties of aluminium bronze in respect to composition of the alloying element in the base alloy (Cu-10%Al) were based on the structure and atomic radius of the alloying elements [16]. Figure 4; generally show that the alloying elements (vanadium and chromium) have good energy absorption. The impact strength of Cu-10%Al alloy increased as the composition of the alloying elements increased.

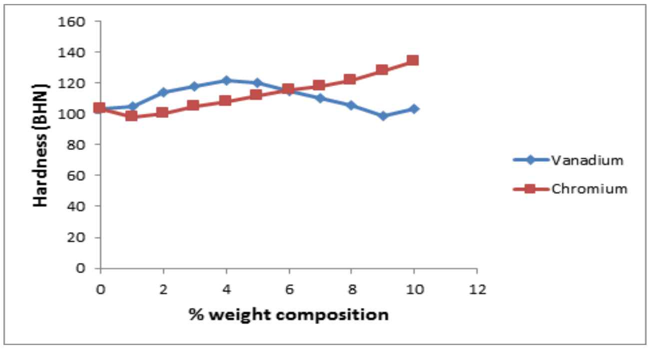

Fig. 3: Effect of alloy compositions on the hardness of aluminium bronze (Cu-10%Al)

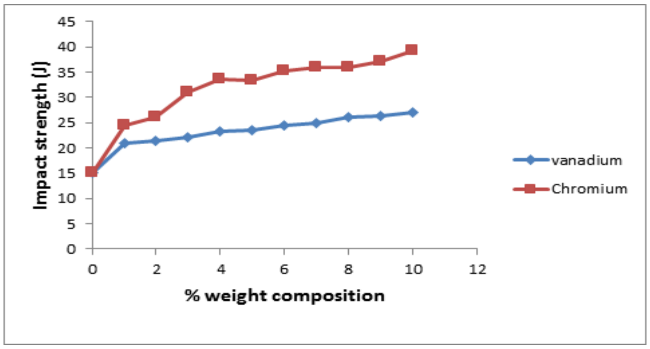

Fig. 4: Effect of alloy compositions on the impact strength of aluminium bronze (Cu-10%Al)

Plate 1-21 represent the micrographs of Cu-10%Al and Cu-10%Al doped with vanadium and chromium of 1-10wt% concentration. It was revealed that the structure consists of α-phase, $\alpha + \gamma_2$ phase, retained β-phase, and particles of element which it was doped with precipitated in α-phase. The α-phase is the region where Al formed solid solution with copper matrix while $\alpha + \gamma_2$ phase is the intermetallic compound. The intermetallic compound (Cu_9Al_4) exists in the form of plate like, precipitate through the α-solution from the grain boundaries. This phase is a hard and brittle compound which has a complicated lattice. The eutectoid $\alpha + \gamma_2$ phase transformed into β-phase.

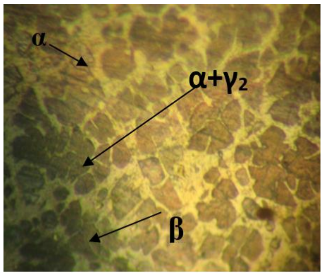

Plate 1 (Cu-10%AL)

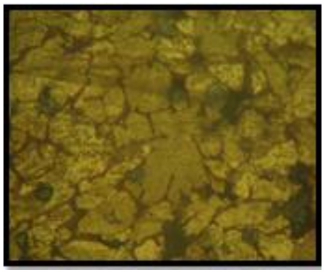

Plate 2

Plate 3

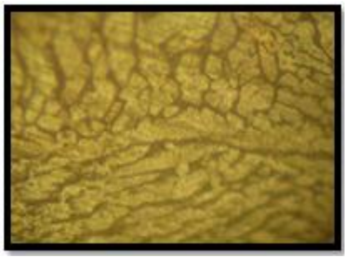

Plate 4

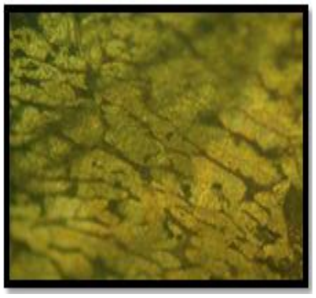

Plate 5

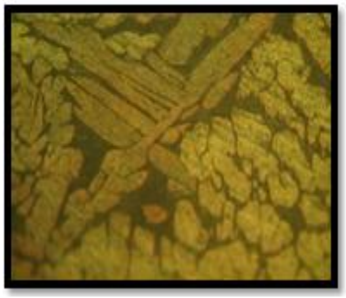

Plate 6

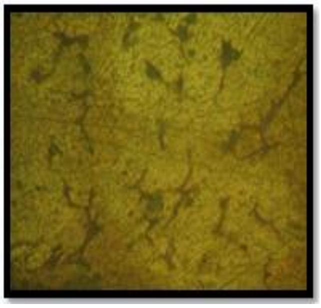

Plate 7

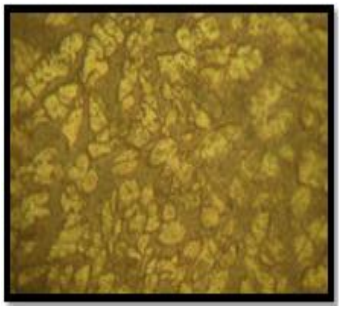

Plate 8

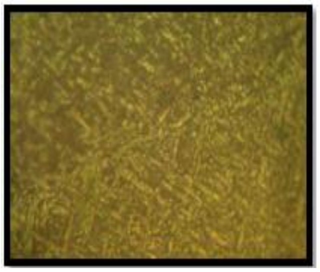

Plate 9

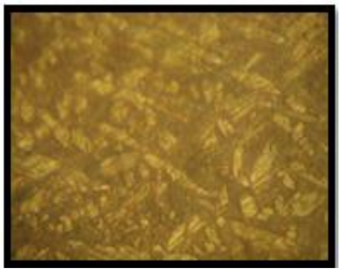

Plate 10

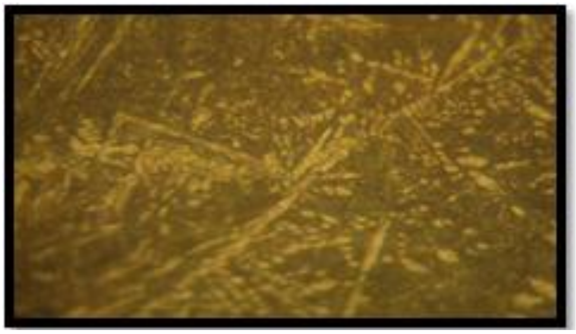

Plate 11

Note: Aluminium- bronze morphologies with/without vanadium at (1) 0% (2) 1% (3) 2% (4) 3% (5) 4% (6) 5% (7) 6% (8) 7% (9) 8% (10) 9% (11) 10%

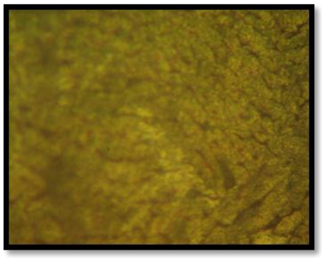

Plate 12

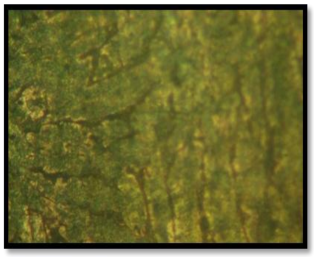

Plate 13

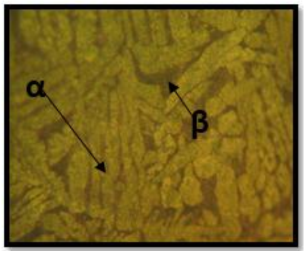

Plate 14

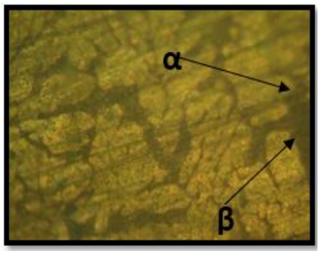

Plate 15

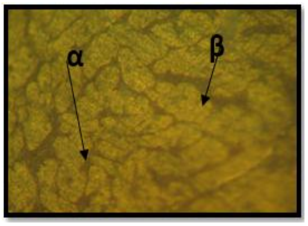

Plate 16

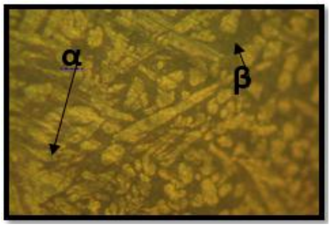

Plate 17

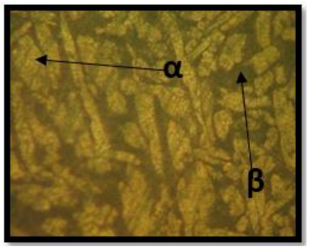

Plate 18

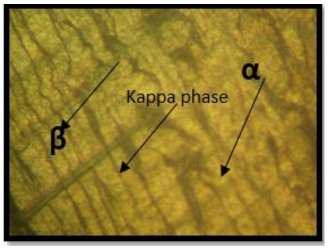

Plate 19

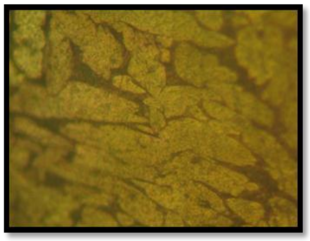

Plate 20

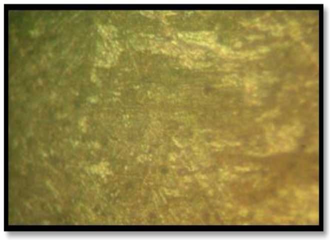

Plate 21

Note: Aluminium- bronze morphologies with chromium at (12) 1% (13) 2% (14) 3% (15) 4% (16)5% (17) 6% (18) 7% (19) 8% (20) 9% (21) 10%

It was observed in plate 1 which is the micrograph of the control sample that the structure consist of large coarse interconnected intermetallic Cu_3Al compound and $\alpha+\gamma_2$ phase. This alloy exhibits the lowest mechanical properties in terms of tensile strength, hardness, impact strength and ductility due to coarse microstructure. In plate 2-11, addition of vanadium to Cu-10%Al increased the formation of retained β-phase which showed small grains of alpha (α) phase and few amount of kappa (k) phase in fine lamellar form. Substantial amount of α-phase and small amount of $\alpha+\gamma_2$ and β phases were observed from 1-6wt% on vanadium addition in the micrograph (Plate 2-7). As the composition of vanadium increased from 7-10wt%, the β-phase predominated over the α-phase region.

From plate 12-21, the micrographs revealed that α-phase increased in size as the composition of chromium increases. This significantly led to the formation of fine lamellar form of kappa precipitates present in the microstructure. The combined effect of Cu-10%Al and chromium suppressed the formation of $\alpha+\gamma_2$ – phase and produced kappa-phase. The kappa-phase precipitating through the α-region has a pronounced effect on the properties of aluminium bronze and considerably increased mechanical properties. The presence of sparse distribution of kappa- precipitates in predominance of $\alpha+\gamma_2$ causes smaller grains to emerge in increasing quantity thereby creating smaller lattice distance which resulted in the improvement of mechanical properties.

Thus, chromium improved ductility, UTS, impact strength, and hardness in composition of 1-10wt%. It was equally noted in Plate 18-21, that the amount of kappa phase within the matrix increased as compared to Plate 2-7 where fewer kappa-phases were observed. This is an indication that presence of more chromium in the system led to increased nucleation sites for the transformation which suppressed the formation of β-phase within the copper lattice, and increased the barrier for dislocation movement.

4. Conclusions and Recommendation

The effect of vanadium and chromium macro-additions on the structure and mechanical properties of aluminium bronze (Cu-10%Al alloy) has been discussed in detail. The research works has shown that aluminium bronze had improved mechanical properties when doped with chromium and vanadium. From this study the following conclusion can be drawn:

- Addition of refractory metal (chromium) increased mechanical properties of aluminium bronze.
- The phases obtained by casting aluminium bronze in a sand mould are α, β, $\alpha+\gamma_{2,}$ kappa phase
- Increasing chromium content of alloy up to 10wt% will increase UTS, impact strength, hardness and ductility.
- By increasing the compositions of the alloying elements, the mechanical properties of aluminium bronze improved which is attributable to change in microstructure of the alloy. This is in agreement with report of Vaidyanath (1980), which stated that complex aluminium bronze tend to stabilize β-phase and effectively permit slower cooling rate when other alloying elements beside Al are present. They modify the structure, improve strength and corrosion resistance, and have a beneficial stabilizing effect on the metallurgical structure and hence, can be used as a substitute for steel in pipeline industry, marine, offshore and shipboard applications.
- Aluminium bronze alloyed with chromium (refractory metal) is recommended for use as a substitute for making propeller in sea-going vessels, landing gear component of aircraft as against aluminium bronze alloyed with vanadium.

5. Acknowledgement

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