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Effect of Cold Rolling and Annealing Treatments on Microstructure, Impact Toughness and Corrosion Resistance of Cu-12Al-2Ni-5Fe NAB Alloy

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ABSTRACT: *In this paper, the effects of cold-rolling and annealing treatments on microstructure, impact toughness and corrosion responses of Cu-12Al-2Ni-5Fe NAB alloy were investigated. The alloy was target material for production of marine boats. The NAB alloy samples were produced by sand casting and cold-rolled to 5 %, 10 %, 15 % and 20 % reductions, and also annealed at temperatures of 350 ^{O}C, 400 ^{O}C, 450 ^{O}C and 500 ^{O}C. Micrographs of the treated NAB samples were obtained, and the samples were also subjected to impact (Charpy) toughness test and electrochemical corrosion test using Tafel potentio-dynamic polarization technique. Results of tests showed improvements in the microstructure resulting in higher impact toughness with degree of cold rolling and annealing temperature. The potentiodynamic polarization curves also indicated improvement in corrosion resistance of the alloy, and corrosion rate reduced with increase in both reduction ratio and annealing temperature, but that the reduction in corrosion rate is higher with cold-rolling treatment. It was concluded that the Cu-12Al-2Ni-5Fe NAB alloy could be a potential substitute for stainless steel in marine boats production and other applications requiring high impact strength and corrosion resistance.*
Keywords: *NAB alloy, cold-rolling, annealing, microstructure, impact toughness, corrosion rate.*

I. INTRODUCTION

Aluminium bronze alloys are one of the versatile engineering materials for applications in corrosive environments and high stress conditions [1]. These belong to a family of copper-base alloys containing approximately 5 - 12 % or sometimes up to 14% by weight aluminium with some optional alloying elements such as Fe, Ni, Mn and Si etc [2, 3]. They are important commercial aluminum bronze alloys combining high strength, good resistance to corrosion and wear, thereby making them one of the most versatile engineering materials. Nickel-Aluminium-Bronzes (NAB) alloys can be specified with a temper anneal heat treatment which helps to ensure a favourable microstructure while maintaining casting properties at optimum levels to improve corrosion resistance ensuring their usage for manufacture of engineering parts such as gears, bearings, dies, valves and propellers [2, 4] as well as plates, sheet, extruded rods and sections [5]. The presence of aluminum by creating a face centre cubic (fcc) phase results to improved mechanical, and hence casting and hot working properties of the alloy [6]. Other alloying elements also assist in modifying the microstructures to obtain improved mechanical properties. The presence of Ni largely improves the corrosion resistance, whereas Fe serves as grain refiner [7].

Steady state corrosion rates for NAB alloys are in the order of 0.025 mm/yr in seawater conditions [6]. The outstanding corrosion resistance of Al-bronzes in marine and chemical processing environments is attributed to the formation of an intrinsic, thin but tough adherent film of aluminium oxide that is self-healing and once formed prevents further oxidation and consequently eliminates flaking so often encountered with ferrous alloys [7, 8].

The aim of this study was to investigate the effect of cold rolling and annealing temperature on, impact tou ghness as well as corrosion behavior of the locally produced Cu12Al2Ni Fe NAB alloy as candidate material for pro duction of marine boats, in simulated seawater under flow conditions using open circuit potential (OCP) and potenti o-dynamic polarization.

II. EXPERIMENTAL PROCEDURES

2.1. NAB Alloy Material

Measured amounts of aluminium pieces were dissolved in molten copper mixed with nickel pieces and heated to 1300 ^{o}C in steel crucibles placed in a lift oil fired furnace. The melt was stirred and sand cast to produce a sound golden yellow nickel aluminium bronze alloy with chemical composition as shown in Table 1. The relatively high iron (Fe) content was attributed mainly to the steel crucible used.

Table 1. AAS Chemical Composition of the NAB alloy

Element	Cu	Al	Fe	Ni	Zn	Others
%	79.75	12.35	5.11	**1.23**	1.20	0.36

2.2. Cold rolling

The cast NAB rods (300 mm long and 20 mm diameter) were subjected to 5 %, 10 %, 15 % and 20 % cold deformation using the Buhler DW Ø80X150 mm miniature rolling machine.

2.3. Annealing Treatments

The as cast and cold rolled samples were annealed at temperatures of 350 ^{O}C, 400 ^{O}C, 450 ^{O}C and 500 ^{O}C in a carbolite muffle furnace. Test samples were heated to the respective annealing temperatures and soaked for 30 minutes after which they were allowed to cool in the furnace for two days to ensure thorough homogenization to remove any remaining dislocations, internal stresses and have a homogenous material.

2.4. Micrographs

Test specimens were polished to mirror surfaces using the SBT Model 900 and Metaserv 2000 grinder/polisher with emery paper of grits 220, 320, 400, 600, 800 and 1200 microns and then etched for 10 seconds in solution of 0.5g potassium dichromate ($K_2Cr_2O_7$), 2ml tetraoxosulphate (VI) acid (H_2SO_4), 10ml water (H_2O) and hydrochloric acid (HCl). Micrographs of the NAB specimens were obtained using ZEISS Observer A1m optical metallurgical microscope at x200 magnification.

2.5. Impact Toughness

Standard Charpy V-notch test specimens of the NAB alloy were prepared and fractured using Avery Denison Izod impact testing machine. Values of the energy absorbed before fracture of the specimens were measured to obtain impact toughness values. A conversion factor of 1.36 was used to convert from feet-pound force (ft-lbf) units to Joules (J).

2.6. Electrochemical Corrosion tests

Corrosion test specimens of the NAB alloy were ground and polished with an exposed surface area of 0.75 m^2. Electrochemical measurements were carried out using AUTOLAB PGSTAT 204N instrument piloted by Nova software [6, 13]. The electrochemical cell was a three-electrode corrosion cell set-up comprising the NAB alloy sample as the working electrode, saturated silver/silver chloride as reference electrode, and platinum rod as counter electrode. The working electrodes were prepared by attaching an insulated copper wire to one face of the sample using an aluminum conducting tape, and cold mounting it in resin. The electrolyte for the investigation was 3.5 % NaCl solution and the corrosion tests were conducted at room temperature. The open-circuit corrosion potential (OCP) measurements were carried out in a separate cell for 30 mins. Potentiodynamic polarization measurements were carried out at a scan rate of 1.0 mV/s with a potential initiated at -250 mV to +250 mV with respect to OCP. The electrolyte was replaced after each experiment.

III. RESULTS AND DISCUSSION

3.1. Microstructures

The microstructures of the cold rolled NAB samples are shown in Figure 1. It can be observed that, the as cast structure has α phase and a martensitic *β*- phase surrounded by lamellar eutectoid phase and a series of kappa phases. Cold rolling causes the *β*- phase on slow cooling to decompose to a eutectoid, consisting of alternate layers of ductile *α* phase and brittle $\gamma 2$ which is pearlitic in nature and increases the strength when in small amount but causes embrittlement when in large amount. At 5 % cold rolling, fine α grains with finely dispersed rosette K_I (Fe_3Al), lamellar shape K_{III} (NiAl) and dendritic rosette K_{II} smaller in size than K_I distributed at the *α/β* boundaries were observed. At 10 % cold rolling, there was predominance of lamellar K_{III} phase formed within the rosette K_I phase all dispersed in the finely divided *α*-phase. At 15 % cold work, dispersion of lamellar shape K_{III}, rosette shape K_I and dendritic rosette shape K_{II} at the *α/β* boundaries was observed while at 20 % cold rolling, there was predominance of rosette shape KI phase in the larger grain size matrix. The precipitation of K-phases in the cold rolled product is responsible for increase in the impact strength and hardness without a decrease in the ductility of the material with best results at 5 % cold rolling [7].

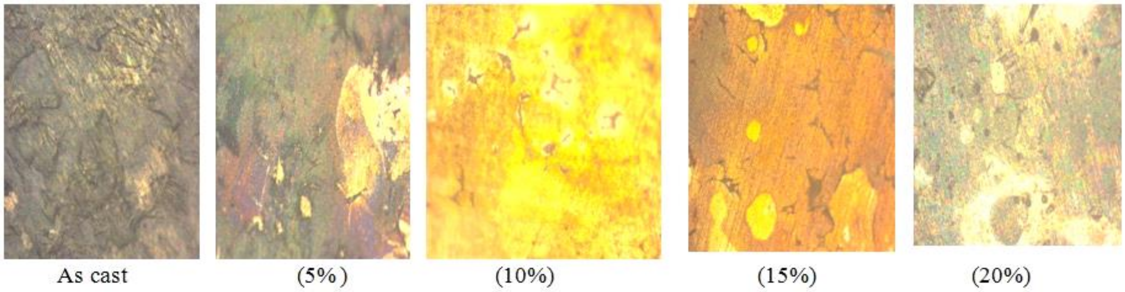


Figure 1: Microstructures of cold-rolled specimens at various degrees of cold rolling

The microstructures of the annealed NAB samples are shown in Figure 2. It can be observed that annealing the cast alloy at 350 ^{o}C results to the dispersion of smaller rosette shape K_{II} phase rich in Fe surrounded by lamellar shape K_{III} phase (NiAl), while, coarse kappa precipitates and micro segregation in the structure at the α/β boundaries was observed at 400 ^{o}C as can be seen in plate VII while at 500 ^{o}C, there was formation of rosette shape K_{I} phase (Fe_3Al) with few dendritic rosette shape K_{II} phase rich in Fe dispersed in the matrix (α/β boundaries). The precipitation of K_{III} phase would usually result to high impact strength [9].

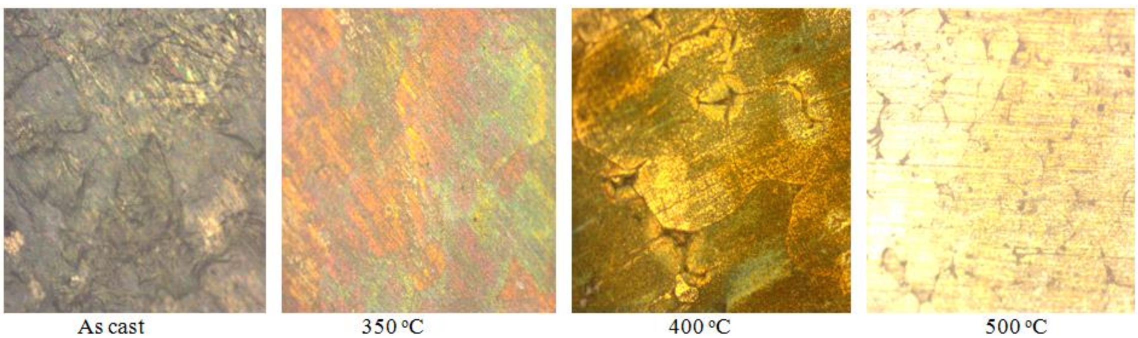


Figure 2: Microstructures of specimens at various annealing temperatures

3.2. Impact Toughness

Figure 3 shows a sudden increase for the 5 % cold rolled NAB sample, and then a gradual increase in impact strength as the degree of cold-rolling is increased. The sudden increase in impact strength at 5 % cold rolling may be attributed to the presence of coherent reinforcing kappa precipitates in the matrix. The microstructure developed in the NAB alloy as a result of cold rolling significantly influenced the impact responses which correspond to the fractions of coherent reinforcing precipitates present in the alloy structure [10]. Figure 4 shows that impact strength increased as annealing temperature is increased. The increase in impact toughness can be attributed to the precipitation of higher number of kappa reinforcing phases in the fine grained α matrix as can be seen in the micrographs of the NAB samples [11].

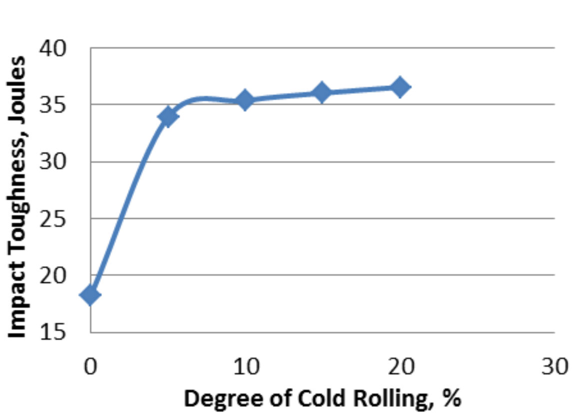


Figure 3: Plot of Impact Toughness against degree of cold-rolling

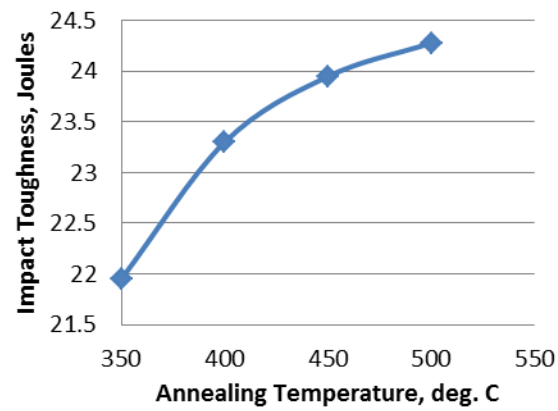
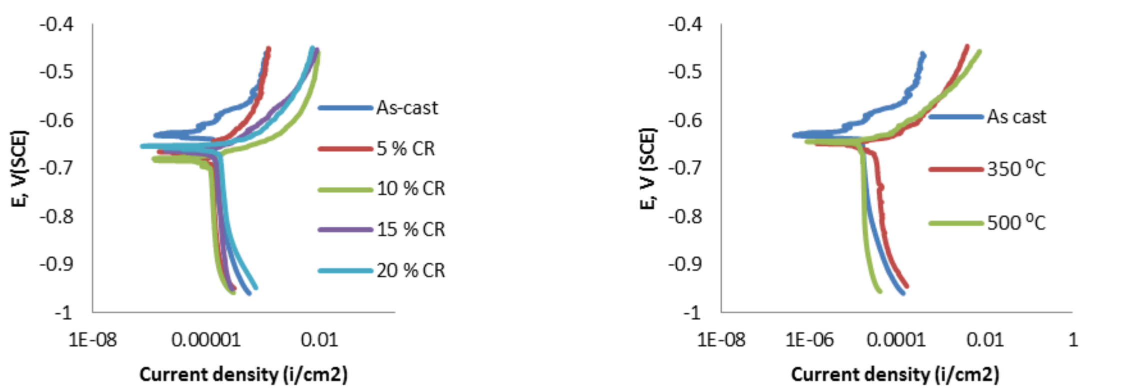


Figure 4: Plot of impact toughness against annealing temperature

3.3 Corrosion Behaviour

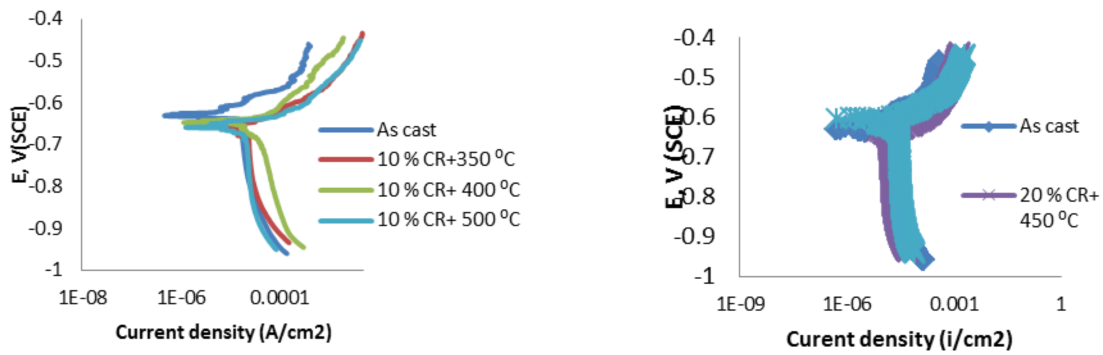
Figure 5 represent the potentio-dynamic polarization curves for cold-rolled and annealed samples. From these figures, the corrosion potential E_{corr} is shifted in the positive direction as degree of cold rolling and annealing temperature are increased. The same trend is exhibited in Figure 6 with the cold rolled, then annealed samples. This indicates that the anodic process is much more affected than the cathodic process. The Tafel slopes remained almost unchanged and suggests that the degree of cold rolling or annealing temperature do not change the mechanism of the corrosion process [12, 13].



(a) Cold-rolled samples

(b) Annealed samples

Figure 5: Tafel Polarization curves for NAB samples



(a) 10 % cold rolled, then annealed (b) 20 % cold rolled, then annealed

Figure 6: Tafel Polarization curves for cold-rolled, then annealed samples

Figure 7 shows that corrosion rate decreased progressively from about 0.2819 mm/yr for the cast sample to 0.1035 mm/yr with increase in degree of cold rolling, and this can be attributed to the reduction in the number of discontinuities on the oxide film as the degree of cold rolling increased, thereby reducing the number of sites where corrosion can be initiated [8, 14]. Similarly, corrosion rate decreased to 0.1895 mm/yr as annealing temperature was increased. This may be attributed to the elimination of casting defects and stresses relief as a result of annealing. The results indicate that more reduction in corrosion rate can be obtained with cold-rolling than by annealing treatments, and that further reduction can be achieved if cold-rolling is followed with annealing treatment by combined action of reduced discontinuities and improved grain structure as evidenced in the resulting microstructures.

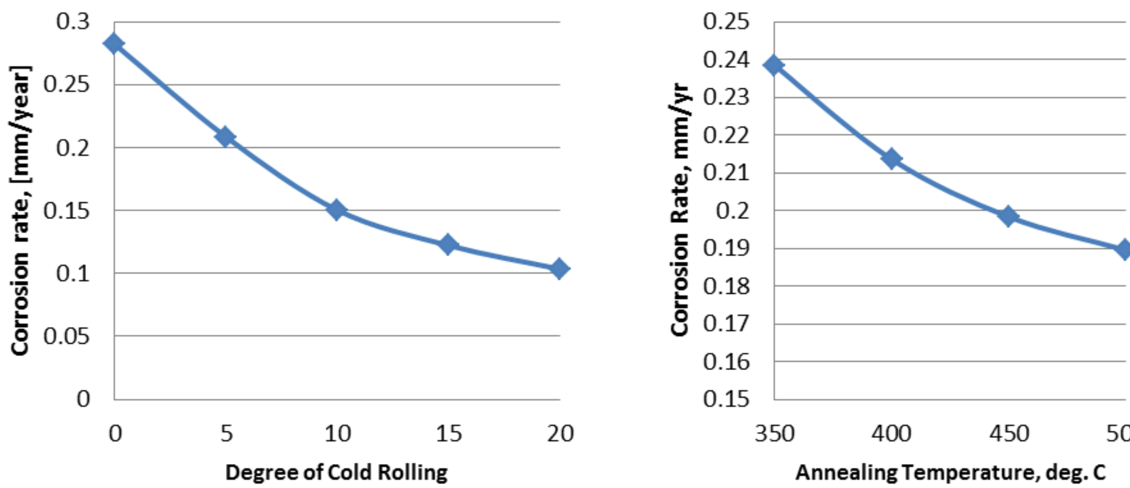


Figure 7: Plot of corrosion rate against degree of cold-rolling and annealing temperature

IV. CONCLUSION

The study has shown that microstructure, impact strength and corrosion resistance of Cu-12Al-2Ni-5Fe NAB alloy are affected by cold-rolling and annealing treatments. The microstructures of the cold rolled and annealed samples showed more reinforcing phases as compared with the as cast sample leading to higher impact strength as the degree (%) of cold-rolling and annealing temperature are in creased. The microstructure of the alloy can be further improved by cold-rolling followed by annealing. Similarly, corrosion resistance of the NAB alloy can be improved by these treatments. Based on these findings, it was concluded that impact strength and corrosion resistance the Cu-12Al-2Ni-5Fe NAB alloy may be improved using cold-rolling and/or annealing treatments for marine boats production and other applications requiring high impact strength and corrosion resistance.

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