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Effect of Copper on Microstructure and Mechanical Properties of Construction Steel

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Abstract**—**Copper being one of the major intrinsic residual impurities in steel possesses the tendency to induce severe microstructural distortions if not controlled within certain limits. Hence, this paper investigates the effect of this element on the mechanical properties of construction steel with a view to ascertain its safe limits for effective control. The experiment entails collection of statistically scheduled samples of hot rolled profiles with varied copper concentrations in the range of 0.12-0.39 wt. %. From these samples were prepared standard test specimens subjected to tensile, impact, hardness and microstructural analyses. Results show a rather huge compromise in mechanical properties as the specimens demonstrated 54.3%, 74.2% and 64.9% reduction in tensile strength, impact energy and hardness respectively as copper content increases from 0.12 wt. % to 0.39 wt. %. The steel's abysmal performance is due to the severe distortion of the microstructure occasioned by the development of incoherent complex compounds which weaken the pearlite reinforcing phase. It is concluded that the presence of copper above 0.22 wt. % is deleterious to construction steel performance.

Keywords**—**Construction steel, mechanical properties, processing method, trace elements.

I. INTRODUCTION

THE development of construction steel of requisite mechanical properties is critical to reliability of structures and safety. These requirements are germane taking into cognisance the production history of the liquid steel from which most construction materials are produced. Although steel is basically an alloy of iron and carbon but, also possesses trace or residual elements which usually impact significantly its mechanical properties. Residual elements in steel are those that remain after refining that are not specifically required and in many cases are considered detrimental to the steel's mechanical properties. This becomes worrisome when such residual elements are present in high concentrations. Some of the residual elements that have proven adverse influence on plain carbon steel from which the bulk of construction steels are made include copper, tin, zinc and lead. The presence of residual elements to a certain percentage has a profound effect on the microstructures and mechanical properties of carbon steels [1]. In particular, copper increases the allotropic and martensitic transformation temperatures proportional to its content [2]. For example, the presence of copper in excess of 0.25 wt% in construction steel usually results in the formation of complex compound causing severe distortions in the steel microstructure thereby compromising the mechanical properties [3]. The effect of copper on the microstructure of mild steel during hot-working has been shown to be tremendous leading to the hot shortness phenomenon [4]. This accounts for the problematic brittle fracture of roll-stock causing frequent mill shut-downs in order to clear from the rollers of fractured pieces of roll-stock. Copper is also known to be responsible for most surface defects of steel due to the preferential oxidation of iron on the surface whereby the steel surface is unduly enriched in copper. Such steels are usually susceptible to chemical ingress when subjected to a temperature range of 1050 – 1200^{0}C [5]. In this condition, the grain boundaries are usually adversely affected leading to the separation of grains by shear thereby compromising the steel mechanical properties. Under oxidising conditions and at concentration of copper not higher than 0.2%, the solubility limit of copper in austenite is easily attained. This condition favours the precipitation of copper in liquid form along the grain boundaries. The tendency for the trapped liquid copper precipitates to escape out of the system is usually rife at elevated working temperature. Hence, the surface defect issue is due to the presence of liquid copper at the scale-metal interface. Similarly, the critical temperature at which inter- granular cracking occurs in mild steel has been demonstrated to be influenced by the amount of copper the steel contains [6]. Often, cracking severity increases with the presence of other residual elements like tin and antimony. These elements are also capable of lowering the solubility of copper as well as the melting temperature of the copper rich-phase. The ubiquitous effect of copper as a residual impurity on construction steel mechanical properties is more pronounced with regard to its marked influence on hardenability thereby impairing toughness resulting to greater difficulties in fabrication. This is because as a weakly austenite stabilising element, copper impedes the decomposition of austenite thereby increasing hardenability. This phenomenon usually gives rise to increase in rolling force as a higher flow stress is required for deformation to occur. The resultant higher mill power consumption often induce additional operation cost and frequent mill down time leading to compromise in the rolled product mechanical properties. Another deleterious effect of copper manifests in steel is weldability that often manifests through the tendency to cold cracking. Welding is one of the fabrication methods by which most construction steel are fabricated hence, the imperative of evaluating the effect of copper on the process. It has been established that the hardenability of the heat affected zone

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(HAZ) is inversely proportional to weldability [7]. Till date, there exists no effective copper removal method available in spite of several attempts at developing an effective copper content mitigation technique [8]. Thus, the industry has witnessed an unprecedented crisis in terms of collapse of structures with attendant loss of lives and property. Given the predominant production of liquid steel employed in the production of construction steel coupled with the prevalence of high concentration of copper in such scraps, it is important that steel millers are properly guided. The present study seeks to establish the best practice processing method for the production of good quality steel as a construction material.

II. METHODOLOGY

A. Process and Material

The secondary steel production process involves the use of assorted steel scraps as a major input. Thus, impurity level in the liquid steel produced thereof varies according to two factors (a) the quality of scrap employed and (b) extent of scrap pre-treatment prior to charging. The materials used for this study were obtained at the downstream stage of production at African Steel Mills (ASM) Ikorodu, Nigeria. ASM is a manufacturer of liquid steel via the electric arc furnace (EAF) with a facility for hot rolling of different construction steel profiles. Several rolling cycles were monitored from start that is, charging of billets into reheating furnace, heating to attain rolling temperature of about 1200^0Cand exit of the billets into the rolling stands till the finishing stage. At the cooling bed, a minimum of five samples were taken from each rolling cycle and subjected to composition analysis using an optical emission spectrometer ARL 3460B model. This was done to track the copper content in the samples and also ensure that the carbon concentration of the samples is relatively the same in order to prevent complications that may arise on the account of disparity in carbon content. Thus, only samples with carbon content in the range of 0.25–0.26wt% were used for the study. Similar attention is given to the silicon and manganese contents making sure that they are not out of range. The silicon content was in the range of 0.17-22wt% while that of manganese is 0.78-0.86wt%. Detail composition analysis results of rolled product samples that conform to these elemental criteria are presented in Table I.

B. Specimen Preparation and Mechanical Tests

There are eight samples made up of one sample containing low amount of copper to serve as reference sample while the remaining seven samples contain copper in amounts adjudged to be relatively high to a varying degrees. The samples are cut at ambient temperature (37^0C) and machined to tensile test specimens according to ASTM A1035/A1035M standards while an Instron electro-mechanical testing machine is used to obtain the specimens relevant tensile data. Hardness test specimens are made in a form compatible with the Rockwell hardness testing method. This is carried out using the “B’’ scale under a load of 10kg as the indenter. The dynamic loading response of the material is simulated through specially prepared Charpy V specimens having 22mm deep notch at 45^0 angle and 0.25mm radius at the base. Each of the specimens is mounted on an Avery impact tester type 3360 with its striking pendulum fixed at a considerable height and at a travelling velocity of $5ms^{-1}$. The value of energy absorbed to fracture each specimen is then read off a dial.

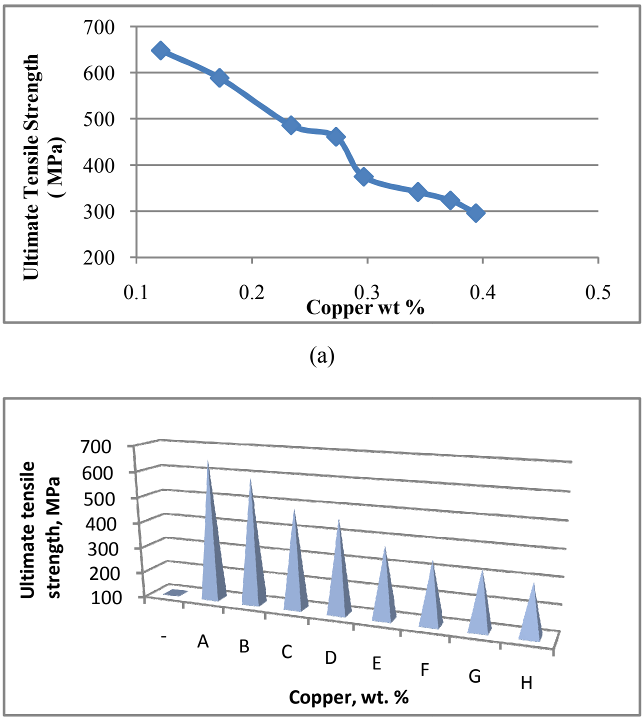
C. Microstructural Analysis

The samples were sectioned and cut into convenient sizes and the surfaces smoothened using a grinder to remove sharp corners or edges. Scratches left by previous grinding were removed on the finest grit paper and washed with water to remove ground particles. Polishing was done with 6μm metadi paste applied to the surface of the samples as polishing abrasive while care was taken not to exert too much pressure to avoid overheating of the specimens after which they were thoroughly washed in running water. Etching was done by immersion in nital (a mixture of 2ml nitric acid and 100ml ethanol) for 30 seconds while the specimens’ microstructural features were examined under an optical microscope at x200 magnification.

III. RESULTS AND DISCUSSION

A. Tensile strength

The tensile strength is the measure of the ability of a material to withstand external applied axial load without fracture. Hence, a key mechanical property that is desirable in a construction material. However, the deleterious effect of the preponderance of composition impurities has been the major challenge of construction steels produced via scraps processing [9]. Figs. 1 (a) and (b) illustrate the effect of copper (one of the major impurities) on the ultimate tensile strength (UTS) of mild steel. As shown in the figure, the steel’s UTS demonstrates a continuous declension in tandem with increase in copper content. The downward UTS trend takes a momentary change around 0.25 wt % - 0.34 wt % due to the increase in microstructural distortion which becomes more pronounced as copper content increases. From this point, 0.30 wt % Copper, the UTS values continue to fall unabated, 360 – 280 MPa. This behaviour stemmed from a near complete severance of inter-atomic cohesion in the microstructure. According to NIS specification of 500 MPa minimum UTS for a construction steel, Fig. 1 shows that only A, B and C specimens exhibited UTS values in the range of 500 –600MPa while the corresponding copper concentrations varied from 0.12 – 0.23 wt %. The implication is that construction steel’s safe tensile strength characteristic is guaranteed only when the copper content does not exceed 0.23 wt %. This agrees well with the NIS standard in which 0.25 wt % Cu (0.03 maximum tolerance) is specified for a construction steel [10].



(a)

(b)

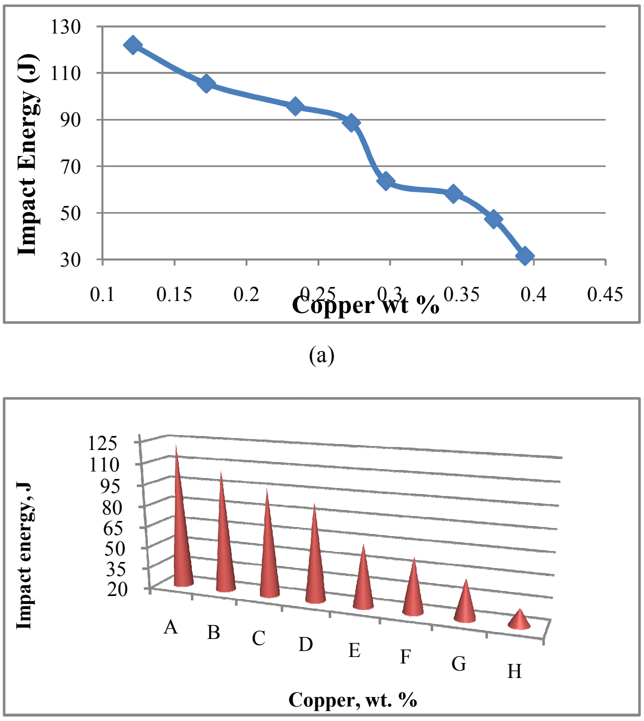
Fig. 1 Effect of copper variation on tensile strength of construction steel

B. Impact Energy

The behaviour of the test specimen under dynamic load with respect to copper content is shown in Figs. 2 (a) and (b). It is observed that the impact energy decreases as the copper content increases. This trend continues up to about 0.22 wt % Cu when dramatic impact energy is demonstrated by test specimens. The major factor responsible for this observation is premised on the severe compromise in the specimen microstructure. The presence of liquid copper precipitate at the grain boundary is incoherent with the pearlite reinforcing phase. This clearly demonstrates that the presence of copper above 0.23 wt % is inimical to its ability to withstand impact load. Incidentally, this type of material is often subjected to various forms of impact in service particularly structures such as bridges, columns and cams decking etc.

C. Hardness

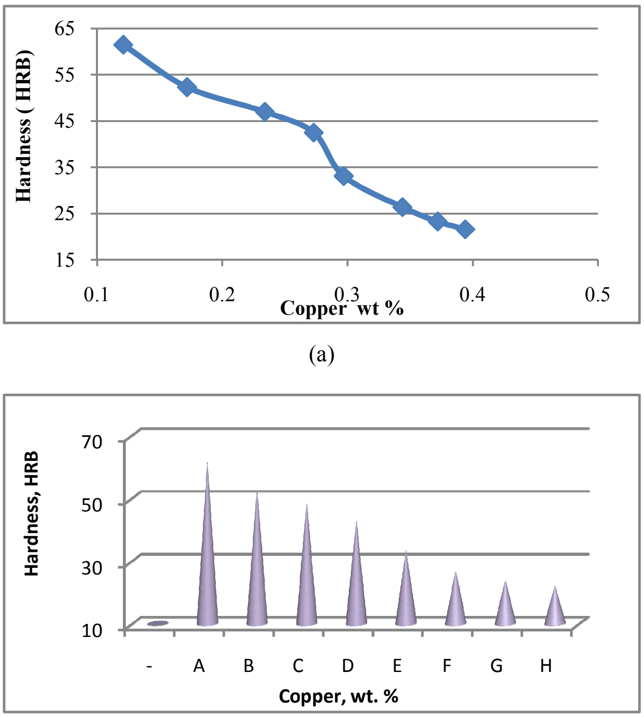
As demonstrated in Figs. 3 (a) and (b), the hardness value decreases gradually from 61.5HRB to 48HRB as copper content increases from 0.12 wt. % to 0.23 wt %. However, beyond this point the curve shows a monotonous decrease in hardness as the copper content increases. This portends a precarious reinforcement-concrete interface load transfer regime due to dwindling surface grip stability of the steel. This behaviour can be explained in the light of copper precipitate interactions within the matrix. The volume fraction of copper impedes austenite transformation such that the eutectic structure is retained at the low temperature similar to the type of structure which subsists during the normal air cooling which further weakens the ferrite matrix causing serious distortions to the grain boundaries which impairs cohesion giving rise to reduction in hardness to 21.6HRB at 0.39 wt% copper.



(a)

(b)

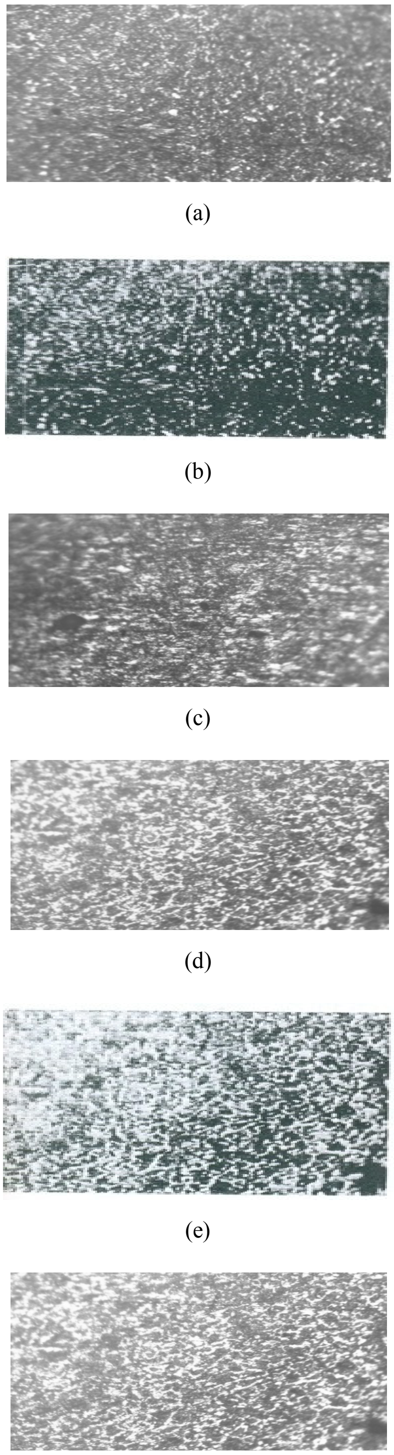
Fig. 2 Effect of copper variation on impact energy of construction steel



(a)

(b)

Fig. 3 Effect of copper variation on hardness of construction steel



(a)

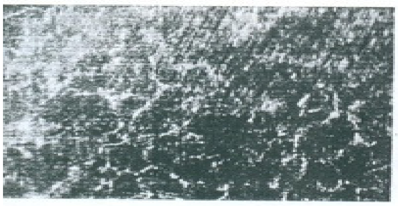
(b)

(c)

(d)

(e)

(g)



(h)

Figs. 4 Micrographs of mild steel specimens containing varied wt. % Cu (a) 0.12 (b) 0.17 (c) 0.23 (d) 0.27 (e) 0.29 (f) 0.34 (g) 0.37 (h) 0.39. The microstructures show clustered rod-like pearlite grains arising from a relatively high copper content

D. Microstructure

The micrographs in Fig. 4 show the extent of microstructural changes that occur with respect to variation in copper content. At 0.12 – 0.23 wt % in Figs. 4 (a)-(c), the effect of copper appears insignificant as the micrographs display fine white crystals homogenously dispersed within the ferrite matrices. However, it is observed that the normal plate-like crystal morphology changes gradually to a somewhat hybrid (pseudo-rod) like crystals in the micrographs containing 0.23 – 0.39 wt % Cu in Figs. 4 (d)-(h). The volume fractions of these incoherent crystals appear to increase as the copper content increases. The pearlite reinforcing phase is in copper content. The pearlite reinforcing phase is inadvertently encapsulated by the liquid copper precipitates shielding the pearlite from effect of load transfer. Thus, the microstructural integrity of these specimens is severely compromised. Given the structure property relationship that governs materials performances, it is obvious that such structure as exhibited by the micrographs in Figs. 4 (d)-(h) are incapable of conferring adequate mechanical properties on a construction steel material.

IV. CONCLUSION

The effect of copper on the mechanical properties of construction steel has been investigated. Results and their analyses have shown that copper, though an intrinsic residual element in this grade of steel is not desirable beyond 0.22 wt %. This is because the mechanical properties investigated namely, ultimate tensile strength, hardness and impact energy exhibited sharp reduction in values as copper content increases from 0.25 wt % - 0.39 wt %. Thus, the performance and reliability of the steel cannot be guaranteed at this composition regime. This must be avoided through meticulous scrap sorting combined with adoption of an efficient melt refining method at the liquid steel making stage.

TABLE I
COMPOSITION ANALYSIS OF SELECTED CONSTRUCTION STEEL SAMPLES

Sample ID	C	Si	Mn	P	S	Cr	Mo	V	Ni	Cu	Al	Fe
						COMPOSITION (wt.%)						
A	0.263	0.220	0.861	0.039	0.033	0.120	0.016	0.003	0.073	0.121	0.031	98.220
B	0.247	0.213	0.793	0.030	0.040	0.110	0.018	0.004	0.078	0.172	0.010	98.285
C	0.252	0.206	0.794	0.031	0.035	0.123	0.020	0.008	0.084	0.234	0.004	98.209
D	0.261	0.190	0.784	0.035	0.040	0.134	0.018	0.008	0.070	0.273	0.012	98.175
E	0.250	0.185	0.860	0.033	0.041	0.100	0.016	0.006	0.084	0.297	0.004	98.124
F	0.258	0.217	0.870	0.030	0.040	0.118	0.018	0.008	0.079	0.344	0.003	98.015
G	0.253	0.192	0.792	0.043	0.039	0.100	0.013	0.002	0.100	0.372	0.005	98.089
H	0.256	0.174	0.846	0.032	0.040	0.100	0.019	0.006	0.102	0.394	0.016	98.015

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