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INFLUENCE OF INDEPENDENT VARIABLES ON THE MECHANICAL PROPERTIES OF ROLLED CARBON STEEL

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Abstract: Mechanical properties of carbon steel are controlled by the ferrite and pearlite fractions, carbon content, grain sizes and strength of both phases. The carbon content affects the pearlite hardness and the hardenability. This work is aimed at studying the effect of chemical composition of ten (10) alloying elements and four (4) sectional sizes (12 – 25 mm diameter) as independent factors on the microstructure and mechanical properties of rolled carbon steels produced from the inland rolling mills. Micro-structural characterization, impact strength and tensile test were made for each section size. The analyses were based on the experimental data from which theEngineers obtain their design data and provide acheck on the standard of raw materials and heat treatment methods being used. It was observed from the studies that the volume of pearlite formed was more in 25mm diameter rods and decreases with reduction in sizes across 20, 16 and 12 mm as a result of the kinetic of cooling. This accounted for the increase in the impact strength from 32J for 25 mm to 100J for 12 mm rods as the sectional size led to lower kinetic of cooling that favoured the proportion of pearlite phase which raises the impact transition temperature and hence, have adverse effect on toughness and ductility. However, the carbon and manganese have pronounced effect in enhancing the tensile strength of 25 mm rods which was 772.72 Nmm^{-2}. But the 12 mm rods seem to have double advantage of both the composition and section sizes which enhanced its strength to 673.16 Nmm^{-2}.

Keywords: Independent variables, mechanical properties, microstructures, rolled steel

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Introduction

Mechanical properties of rolled bars are controlled by many metallurgical factors, such as the volume fraction of different phases (pearlite (V_P), martensite (V_M) and ferrite (V_F)); the carbon content of pearlite phase, martensitic phase, grain size of the pearlite, martensite and ferrite. The strength of the phases is strongly affected by the chemical composition of the steel (Valeria *et al.*, 2015). In developing countries like Nigeria, there is increasing demand for structural steel material of high quality for the construction sector in order to meet up with the continuous growth and development of infrastructures. The continuous wide uses as prospective functional and structural materials are because of their high strength, wear resistance and relatively low material cost among others (Adnan *et al.*, 2010).

The productions of quality reinforcement steel bars for structural applications by the inland rolling mills remain one of the challenges facing the conventional mill operators. This can be overcome by ensuring that some parameters such as composition and section sizes are given the required considerations in design to ensure optimal performance in service. The parameters collectively determine the microstructures, phases present, their volume; and invariably the mechanical properties of the rolled bars. The microstructures and the mechanical properties of as-rolled products from every conventional rolling mill are determined primarily by the chemical composition and section sizes.

In hot rolling mill operation, the material stock, that is, slab, bloom or billet, is subject to deformation by different combinations of forces (compressive, tensile, torsional, abrasive, shear) at high temperature tribology. In most intakes, the mill processing imposed technical defects and imperfection on the final mill production, which consequently results in mechanical failure of rolled products under structural and constructional applications.Adnan *et al.* (2010) had studied the effect of carbon content on the mechanical properties of medium carbon steels while Jenan 2014 established that cooling rate has effect on the mechanical properties of carbon steel which was also in agreement with Krzyszt of *et al.* (2006) that researched on the effect of grain refinement on mechanical properties of micro-alloyed steels. The work of Valeria *et al.* (2015) focused on the effect of carbon content on microstructure and mechanical properties of dual phase steels.

Consequently, theunderstanding of the influence of chemistry and physicsof material on its overall effects on the microstructures in relations with other relevant parameters and mechanical properties are pre-requisite for design and applications. The purpose of this workwas to explore the relationship between the mechanical properties and chemical composition in conjunction with section sizes of rolled steel from the nation’s rolling mill.At times, at great strains in uniaxial tension, materials experience anisotropic reorientation of the minute scale microstructures and very big stresses can be achieved prior to final break. Thus, one of the major noticeable but still the most complicated predicaments in dealing with failure is in defining the yield stress σ_y and the failure stress (strength) (Cottrell, 1981; Hull and Bacon, 2001); both properties are essential to calibrate failure factors. Such properties as modulus E, yield stress σ_y, and strength σ_{UTS} are generally codified (worked out) and estimated (Christensen, 2011).

The yield stress, σ_y, is the particular point on the stress strain curve at which the tangent modulus, E_T, changes with respect to increasing strain ϵ at the highest rate. The expression in (A) is a satisfied condition for the yield stress σ_y (Christensen, 2008).

$$\sigma = \sigma_y \text{ at } \frac{d^2\sigma}{d\epsilon^2} = \max \qquad \text{(A)}$$

or

$$\sigma = \sigma_y \text{ at } \frac{d^2\sigma}{d\epsilon^2} = 0 \qquad \text{(A)}$$

Christensen (2011) established for ductile metals that the location of the maximum of the second derivative is that condition at which the dislocation flow is adequately intense and varied as to cause this result; which process point involves both dislocation nucleation and the actual dynamics of the flow.

Using a typical stress-strain curve to evaluate the derivatives in (A); the strain is decomposed into elastic and plastic parts, it gives (B) which represents a continuous function with continuous derivatives in accordance with most physical observations.

$$\epsilon = \frac{\sigma}{E} a \ln\left[1 - \left(\frac{\sigma}{\sigma_0}\right)^m\right] \qquad \text{(B)}$$

where a, m, and σ_o are specified parameters.

However, from diverse varieties (C) was selected as a simple but dependable operational way of determining the yield stress; which is refer to as that stress at which the actual strain is 0.05 greater than the linear elastic projection (outcrop).

$$\sigma = \sigma_y \text{ at } \frac{\epsilon_y - \epsilon_L}{\epsilon_y} = 0.05 \qquad \text{(C)}$$

where: ϵ_L is the linear range of elastic strain.

Knowing the true stress to be the ratio of applied load to the instantaneous cross-sectional area over which deformation (necking) occurs, it is more convenient to represent strain as true strain.

The true and engineering stress and strain are interrelated according to (D) and (E) that are valid only to the start of necking;

$$\sigma_T = \sigma(1+\epsilon) \qquad \text{(D)}$$

$$\epsilon_T = \ln(1+\epsilon) \qquad \text{(E)}$$

Elastic deformation would occur when stress and strain are proportional. The larger the modulus, the stiffer is the material, or the smaller the elastic strain outcome from the applied stress. On a minute size, very large elastic strain manifests as little changes in the interatomic spacing and the stretching of interatomic bonds. As a result, the size of the modulus of elasticity measures the resistance to separation of adjoining matter (atoms/grains). The yield strength is usually used when the strength of a metal or alloy is intended for design purposes. On the other hand, toughness commonly speaking, quantifies the ability of a material to absorb energy up to fracture. The geometry and the mode of load application are imperative in determining the toughness. For high strain rate loading situations and as a notch is in attendance, notch toughness is assessed by using an impact test.

Materials and Methods

Materials and equipment

The rolled carbon steel rods used for the research work were obtained from Nigerian Rolling Mills – Ajaokuta Steel Rolling Mills. The rods used were of diameters 12, 16, 20 and 25 mm. Other materials included abrasive papers, emery cloth, and diamond paste, water as coolant, etchant, cotton wool and desiccators. The equipment included lathe machine, Metaserv 2000 electric table grinder, electric polishing machine of model 900 (South bay technology) and a high magnification Nikon-Eclipse M600 model optical microscope with digital camera attached.

Methods

Twelve different compositions of steels were produced from three batches of discharge. The molten steels were cast to 100 mm x 100 mm square billets in three different batches. The billets were rolled to rods of four (4) different diameters as 12, 16, 20 and 25 mm. Istron Universal tensile tester of model type 3369 was used to carry out the tensile tests. The test specimens were machined to the machine's specification in accordance with ASTM standard. Each specimen was gripped at the two ends and then pulled until fracture and the ultimate tensile strength was recorded on the panel. The impact energy was determined by using Tinius Olsen model 84-3 impact tester. The test piece of a square cross-section of 10 mm dimension and 50 mm long, notched at the midpoint was used. The specimen was placed in a vice as a beam fixed at the two ends. The pendulum hammer of 75 kg weight was raised, on releasing; the specimen was hit behind the V-notch. The energy absorbed was read from the dial scale mounted on the machine and computed as a difference between the initial height h and final height h^i as the measure of the energy absorbed. The chemical compositions of the as-rolled specimens were determined using model 2000-3 Spetro-CJRO Arc-Spectrometer. Rod specimens obtained from the rolling mill were sectioned into small sizes for the grinding and polishing. Soluble oil water coolant was continuously applied to lubricate the specimens and prevent any alteration in the original structures. The samples for the micro-structural analyses were ground using an abrasive wheel to obtain an averagely flat surface and washed off with running water to remove any loose grit. The surfaces were ground using a series of 220, 320, 400 and 600 µm grits silicon carbide papers. Excessive deformation of the surface was however prevented during the grinding by applying only light pressure on the specimens (Fadare *et al.* 2011). The surface polishing was done with 800 and 1000 µm grits emery papers and finally with the emery cloth using diamond paste to achieve a mirror-finish appearance. The surfaces were water swab for 3 seconds after and rinsed in methylated spirit to remove water stain from the surfaces and finally dried in warm air. The etching was done using Nital (2% of Nitric acid and 98% ethanol) (Khanna, 2009). The microstructures were examined following standard procedures at x400 magnifications (M). The M was determined by quantitative metallography according to ASTM E562. The metallographs are shown in Plates 1-4.

Results and Discussion

The result of the chemical analysis of the rolled carbon steel used is contained in table 1 while that of the mechanical test carried out and the effect of the variables on the properties are as shown in Table 2. Plates 1 – 4 showed the results of micro-structural analyses carried out. Fig. 1 indicates the variation of the alloying elements with sizes of rolled carbon steel rods while Fig. 2 explains the effects of sizes on the mechanical properties of the rolled carbon steel but Fig. 3 analysed the effect of elemental composition on mechanical properties of rolled steel rods.

Table 1: Chemical compositions of as-rolled carbon steels samples

Batch	Size (mm)	%C	%Mn	%Si	%P	%S	%Cr	%Ni	%Cu	%Co	%W	%Fe
A11	12	0.359	0.72	0.171	0.016	0.015	0.78	0.08	0.221	0.038	0.157	97.443
B11	12	0.357	0.63	0.101	0.016	0.015	0.69	0.08	0.276	0.016	0.158	97.661
C11	12	0.355	0.74	0.18	0.016	0.014	0.72	0.07	0.249	0.024	0.158	97.474
A21	16	0.358	0.62	0.18	0.041	0.039	0.019	0.075	0.25	0.031	0.148	98.239
B21	16	0.359	0.6	0.19	0.039	0.038	0.021	0.074	0.27	0.028	0.147	98.234
C21	16	0.362	0.67	0.2	0.038	0.042	0.017	0.074	0.26	0.019	0.151	98.167
A32	20	0.389	0.68	0.16	0.042	0.031	0.015	0.026	0.251	0.016	0.121	98.269
B32	20	0.391	0.67	0.18	0.04	0.028	0.018	0.021	0.248	0.014	0.11	98.28
C32	20	0.39	0.61	0.17	0.041	0.031	0.011	0.072	0.253	0.022	0.119	98.281
A41	25	0.422	0.691	0.224	0.031	0.042	0.01	0.021	0.248	0.018	0.158	98.135
B41	25	0.415	0.685	0.219	0.03	0.041	0.01	0.02	0.248	0.017	0.156	98.158
C41	25	0.418	0.72	0.222	0.032	0.038	0.01	0.02	0.252	0.018	0.158	98.112

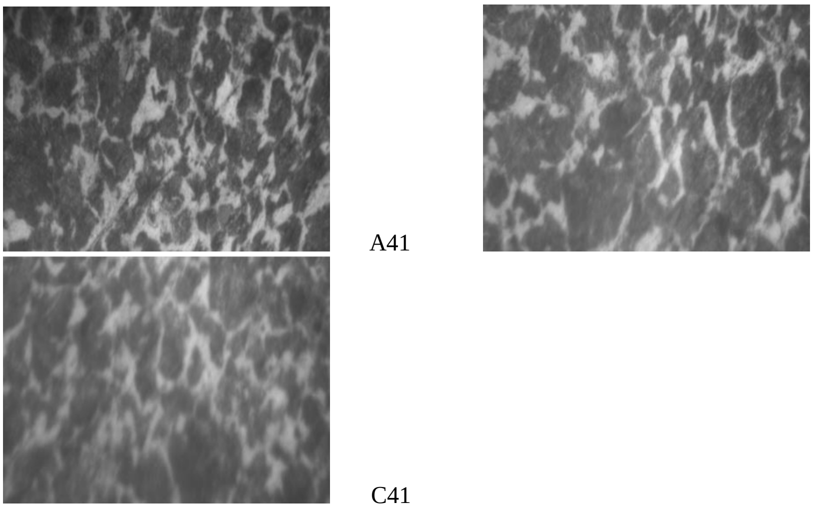
Table 2: Mechanical properties of rolled carbon steel samples

Batch	Section Sizes (mm)	Tensile Strength,TS $_{@maxL}$	Tensile Strength,TS$_{@Break}$	Yield Strength	Impact Strength
A11	12	602.84	469.84	452.71	84
B11	12	673.18	494.83	486.31	100
C11	12	637.88	482.34	469.51	100
A21	16	590.16	473.55	445.64	65
B21	16	567.26	448.99	406.73	52
C21	16	578.71	461.27	426.19	52
A32	20	638.06	551.84	406.73	50
B32	20	644.67	579.78	424.42	45
C32	20	641.37	565.81	415.58	48
A41	25	772.72	671.14	459.19	30
B41	25	673.87	611.87	397.89	42
C41	25	723.30	641.51	428.84	32

Effect of sample sizes and chemical composition on the mechanical properties

Usually, in metal alloys, microstructure is distinguished by the number of phases present, their proportions, and their manner of distribution or arrangement. The microstructure of an alloy is dependent on such variable factors as the type and concentrations of alloying elements present, and the heat treatment of the alloy (the temperature, the soaking time at particular temperature, and the regime of cooling rate to room temperature).

The structures of Plates 1 - 4 showed that the materials consist of pro-eutectoid ferrite and pearlite. The pearlite is the grey coloured phase while the ferrite appeared as white (Fadare *et al.*, 2011); with 25 mm diameter size containing more pearlite than the others. The trend was followed by 20, 16 and 12 mm rods. This suggests that they experienced a relatively slow cooling regime to avoid the formation of metastable phases. However, the morphology was governed by the kinetic of cooling. In addition to alloy composition, the cooling regime has effect on the properties. The former depends on the rate of heat energy extraction, which is a function of the characteristics of the cooling medium in contact with the specimen surface, the specimen size and geometry (Balogun *et al.*, 2011). In the present study, these microstructures were obtained primarily because the materials were plain carbon steels. The trace alloying elements did not play dominant roles in influencing the structures. However, they might have some influences on strengthening role. In rolling, metals may undergo plastic deformation under the effects of applied compressive, shear, and torsional loads.

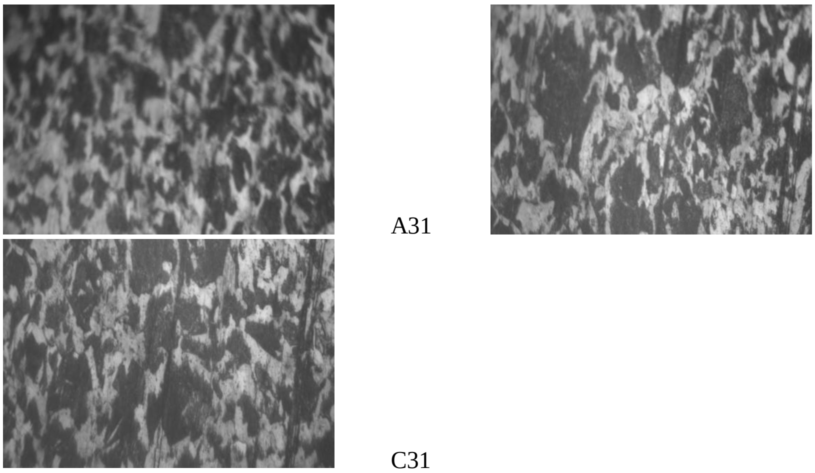


A41

B41

C41

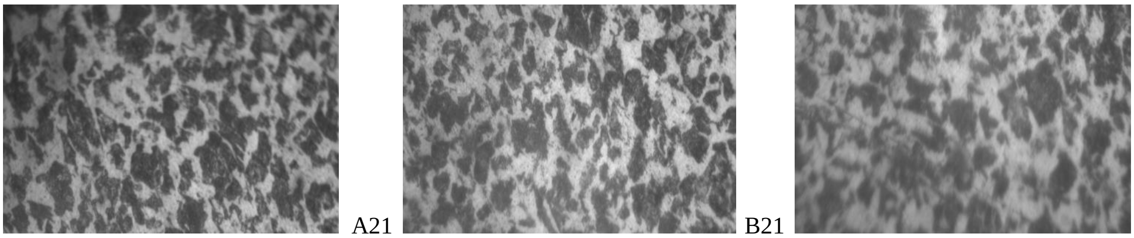
Plate 1: Microstructures of 25 mm diameter of as-rolled carbon steel (x400)



A31 B31

C31

Plate 2: Microstructures of 20 mm diameter of as-rolled carbon steel (x400)



A21 B21 C21

Plate 3: Microstructures of 16 mm diameter of as-rolled carbon steel (x400)

A11 B11 C11

Plate 4: Microstructures of 12 mm diameter of as-rolled carbon steel (x400)

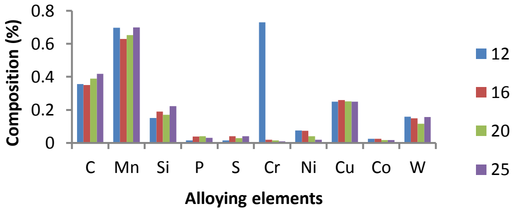


Fig. 1: The variation of alloying elements with sizes of rolled carbon steel rods

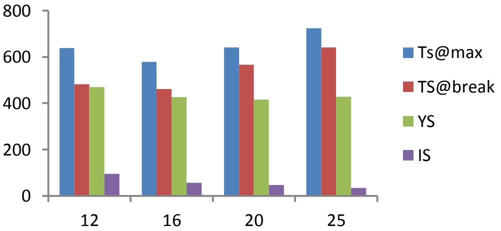
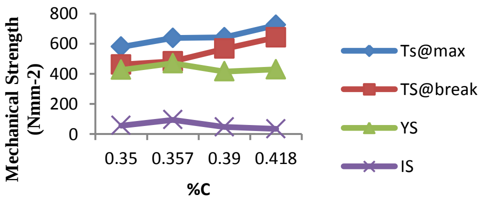
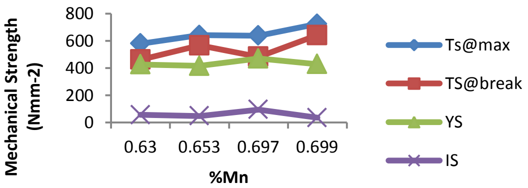


Fig. 2: The effects of sizes on strength properties of rolled carbon steel





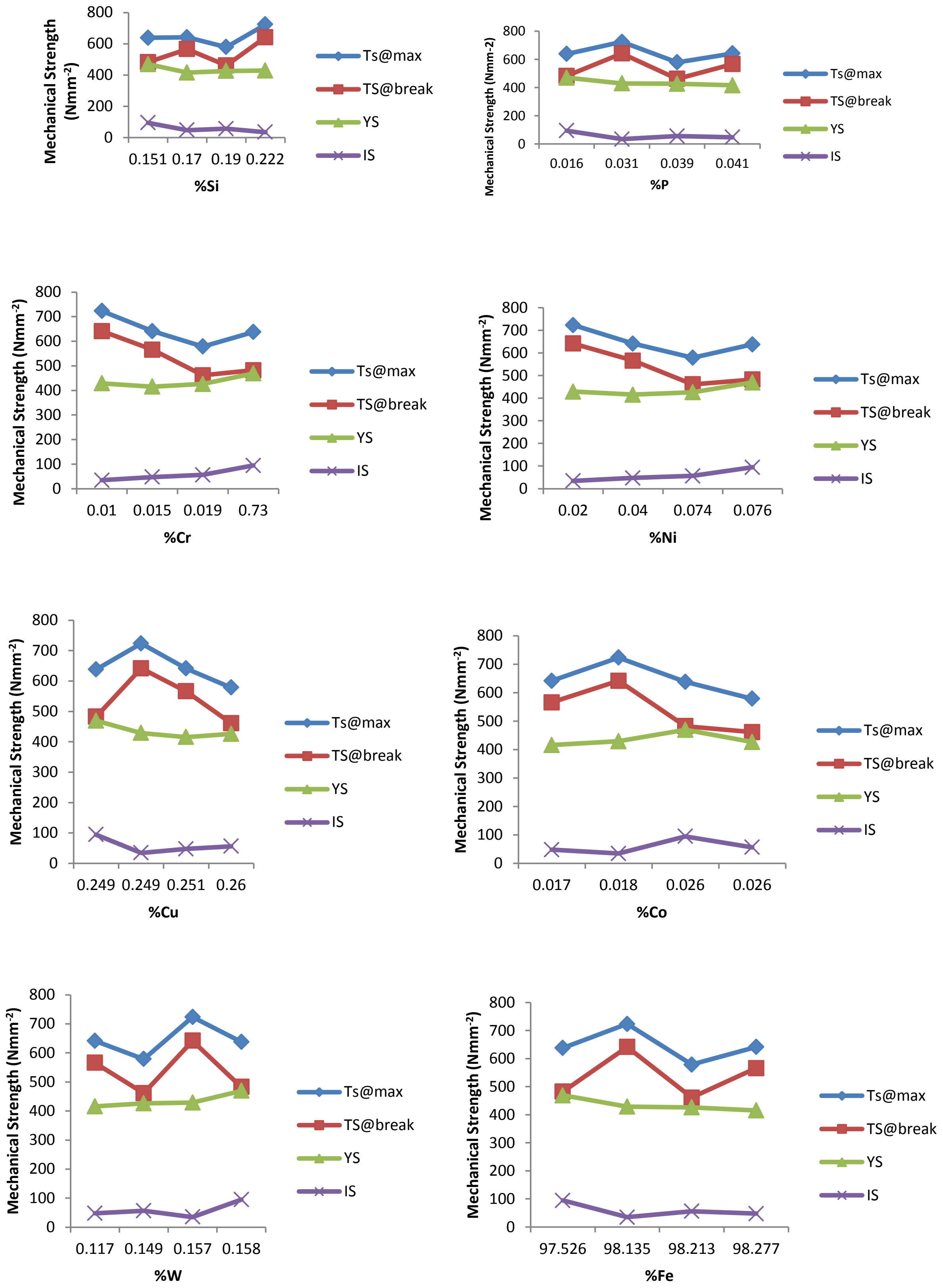


Fig. 3: Effect of elemental composition on mechanical strength properties of rolled steel rods

The mechanical properties of carbon steels are essentially dependent on the content of carbon (0.05% – 1%) and manganese (0.25% - 1.7%) (ASM Metal Handbook, 1998). Therefore, the concentrations of these two elements in Table 1 showed that they are responsible for the higher strength values of 673.18 Nmm^{-2} obtained for 12 mm rod than 590.16 Nmm^{-2} for 16 mm rod. This was as a result of the extent of its grain size refinement effect. In the 12 mm diameter rod, due to its smaller size, it experienced a much higher degree of under-cooling which is dependent on dimension, hence, leading to its finer grain size as against 16 mm diameter rod that experienced a comparatively lower kinetic of cooling. Therefore, there was grain growth in 16 mm rod more than 12 mm diameter rod had experienced. This also accounted for the relatively higher yield strength of 486.31 Nmm^{-2} and tensile strength for 12 mm rod than 445.64 Nmm^{-2} for 16 mm rod which is in agreement to the scientific analysis of the relationship between grain size and strength of Hall-Petch and the theory of yield point that involved the breaking away of dislocation from interstitial carbon atmosphere.

The phase diagrams for alloy systems show relationship between the microstructure and mechanical properties, and provide useful information as regards melting, casting, crystallization, and other occurrences. The grain size effect on yield strength can consequently be explained by assuming that a dislocation source operates within a crystal causing dislocations to move and eventually pile up at the grain boundary. It therefore determines the distance dislocations have to move and the number of grain boundary to be crossed in order to propagate. This implies that the bigger the grain size, the easier it is to propagate the yielding process. It therefore holds practically that the finer the grain size, the higher the resulting strength (Krzysztof *et al.*, 2006).

However, in the case of 20 and 25 mm diameter rods, the 25 mm rod displayed higher strength of 772.72 Nmm^{-2} than 644.67 Nmm^{-2} for 20 mm rod. And this might be due to the effect of composition. The 25 mm rod contains higher content of 0.422% carbon and 0.691% manganese than 0.391% carbon and 0.67% manganese for 20 mm rod. These two elements are strengtheners. Though, the cooling effect would have favoured 20 mm rod to have higher strength value, but the composition had a dominant effect on it. The same trend of the tensile strength was observed in the yield strength and tensile strength at break. The fracture toughness was observed to be different as shown in Fig. 2. The lowest value of 30J for impact strength was recorded for the 25 mm rod despite having highest values of tensile properties. This resulted from the sectional size that led to lower kinetic of cooling which favoured largest proportion of pearlite and the phase has been known to have adverse effect on toughness and ductility of carbon steels (Jenan, 2014). The higher the pearlite content, the more the impact transition temperature is raised and the less the impact energy absorbed. This is because the presence of pearlite in the micro-structure provides sites for easy nucleation of cracks, particularly at the ferrite-cementite interfaces. However, crack would only propagate a short distance in ferrite before encountering another cementite-lamella. Energy is absorbed during the propagation. The resultant effect is that there is a wide transition temperature which implies that the low energy absorbed in the overall impact tests on the more pearlite structures arises from the fact that many nuclei would have occurred at the pearlitic interface which, together with the high work hardening rate, restricts plastic deformation in the vicinity of the crack.

Conclusions

From the results, it could be observed that these independent variables have significant effect in influencing the microstructures of the products. The grain refinement due to the smaller diameter size was responsible for the 673.18 Nmm^{-2} obtained in the 12 mm rod while the higher content of 0.422% carbon dominantly resulted in higher strength of 772.72 Nmm^{-2} for 25 mm rod. The drop in the strength of the 16mm recorded was due little grain growth experienced from the lower kinetic of cooling compared to that of 12 mm rods. They were governed by the rate of cooling as dictated by the section diameters (sizes) and chemical composition of the rolled carbon steel bars and hence, have combined influence on their mechanical properties.

References

Adnan C., Akin D., Osman S. and Nazim U. (2010). Effect of Carbon Content on the Mechanical Properties of Medium Carbon Steels. Verlag der Zeitschrift f¨ur Naturforschung, T¨ubingen· http://znaturforsch.com. 0932–0784 / 10 / 0500–0468 $ 06.00 Pp 468-472.

ASTM E23. 2008, Standard Test Method for Izod Bar Impact Testing of Metallic Materials, American Society of Testing and Materials.

ASTM E8. 2008, Standard Test Method for Tension Testing of Metallic Materials, American Society of Testing and Materials.

Balogun SA, Lawal GI, Sekunowo OI &Adeosun SO 2011. Influence of finishing temperature on the mechanical properties of conventional hot rolled steel bar. *J. Engr. & Techn. Res.*, 3(11): 307-313.

Christensen RM 2008. Observations on the Definition of Yield Stress.*Acta Mech.,* 196: 239-244.

Christensen RM 2011. Defining Yield Stress and Failure Stress (Strength), Failure criterial.com.

Cottrell AH 1981. The Mechanical Properties of Matter. Krieger, Malabar, FL.

Fadare DA, Fadara TG & Akanbi OY 2011. Effect of Heat Treatment on Mechanical Properties and Microstructure of NST 37-2 Steel. Journal of Minerals & Materials Characterization & Engineering, Vol. 10, No.3, Pp.299-308. jmmce.org

Metals Handbook Desk Edition, Second Edition 1998. ASM International, pp. 153-173. www.asminternational.org. Davis, J. R. Editor.

Hull D&Bacon DJ 2001. Introduction to Dislocations. Butterworth Heinmann, Oxford.

Jenan MN2014. The Effect of cooling rate on mechanical properties of carbon steel (ST 35). *Diyala J. Engr. Sci.*,7(1): 109-118. ISSN 1999-8716.

Khanna OP 2009. Materials Science and Metallurgy. Dhanpat Rail Publication Limited, New Delhi,pp. 17-12.

Krzysztof Muszka, Kanusz Majta and Lukasz Bienias (2006). Effect of Grain Refinement on Mechanical Properties of Microalloyed Steels. Metallurgy and Foundry Engineering, Vol 32, No 2

Valeria L de la Concepcióna, Hernán N, Lorussoa B, Hernán G & Svobodab C 2015. Effect of carbon content on microstructure and mechanical properties of dual phase steels. International Congress of Science and Technology of Metallurgy and Materials, SAM-CONAMET 2013. Procedia Materials Science 8 (2015) 1047 – 1056. Available online at www.sciencedirect.com