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Full Length Research Paper

Influence of finishing temperature on the mechanical properties of conventional hot rolled steel bar

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The conventional mill operators are faced with challenges of producing reinforcing steel bars of adequate strength characteristics. This stems from the inability to effectively control and monitor process variables such as temperature, strain-rate and cooling. These parameters collectively determine the microstructure and invariably the mechanical properties of the rolled bars. However, the finishing temperature appears to be more important than the temperature at the roughing stand. Often, the type and extent of in-process cooling method and duration of each rolling cycle largely determine the finishing temperature. Thus, installation of temperature monitoring devices along the rolling line will furnish prompt thermal information necessary for both process conditions and product properties optimization respectively. Detailed temperature tracking of a conventional rolling operation was carried out with a view to establish the range of finishing temperature that give rise to improved strength characteristics of steel bars produced, taking cognizance of the rolling stock chemistry. Improvement in the bars mechanical properties was achieved within 840 to 860˚C finishing temperature and rolling stock chemistry in the range of 0.21 to 0.23% C, 0.20 to 0.25% Si and 0.50 to 0.60% Mn.

Key words: Rolling**,** temperature, microstructure, steel, strength.

INTRODUCTION

In hot rolling of steel, temperature is the dominant parameter controlling the kinetics of metallurgical phenomena such as flow stress, strain-rate and recrystallization (both static and dynamic). The mechanical properties of the final product are determined by a complex sequence of microstructural changes conferred by thermal variations (Pereloma, 2001; Richard, 2001). Temperature also aids the softening mechanism by which rolling stocks (billet) are prevented from brittle fracture due to work hardening effect of the rolling forces.

There exist in hot rolling, a correlation between strain-rate and the flow stress. The working temperature however, influences both phenomena such that increase in temperature usually results in increased strain rate, which eventually affects the austenite grain size (Choi, 2002). Unless by means of innovative cooling, the austenite grain size at the last pass solely determines the product grain size and mechanical properties.

Most mills in developing nations of the world still operate on the basis of conventional rolling which is devoid of modern facilities offered by controlled rolling (Obikwelu, 1987). Usually, conventional mill operations are not executed along with the necessary temperature monitoring with a view to controlling the evolved microstructure. Hence, steel bars produced through conventional rolling often exhibit abysmally low mechanical properties (Lamberterie, 2006; Saroj, 2000). Control of inter-stand temperature such that the desired initial austenite grain size is achieved at the last stand is imperative. This will ensure that appropriate phase transformation of the right grain size, morphology and texture is obtained during cooling of the bars.

The above notwithstanding, control of temperature during rolling is more important at the finishing than at the roughing stage (Laasraoui and Jonas, 2007). Choi (2002) also established that property sensitive parameters of hot rolled steel bar depend largely on the finishing temperatures.

The idea was employed (Barrett and Wilshire, 2002) in the early 1980s in the production of ferritic hot rolled interstitial free steel to eliminate temperature control problems. This was accomplished by reducing the

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Table 1. Chemical composition analysis of rolling stocks (billets).

Sample ID	Elements (%)												
	C	Si	S	P	Mn	Ni	Cr	Sn	Mo	V	Cu	Fe	Ceq
A	0.194	0.167	0.039	0.025	0.856	0.146	0.178	0.038	0.029	0.006	0.344	97.978	0.42
B	0.220	0.199	0.046	0.032	0.501	0.101	0.104	0.036	0.015	0.003	0.216	98.454	0.35
C	0.164	0.123	0.046	0.027	0.768	0.137	0.149	0.037	0.017	0.002	0.318	98.336	0.36
D	0.308	0.258	0.050	0.028	0.684	0.117	0.147	0.037	0.015	0.002	0.342	98.012	0.49
E	0.211	0.246	0.039	0.028	0.506	0.112	0.148	0.035	0.013	0.002	0.306	98.354	0.36
F	0.172	0.113	0.046	0.019	0.697	0.105	0.136	0.035	0.019	0.001	0.249	98.686	0.34
G	0.231	0.250	0.055	0.034	0.602	0.102	0.120	0.034	0.020	0.002	0.274	98.276	0.38

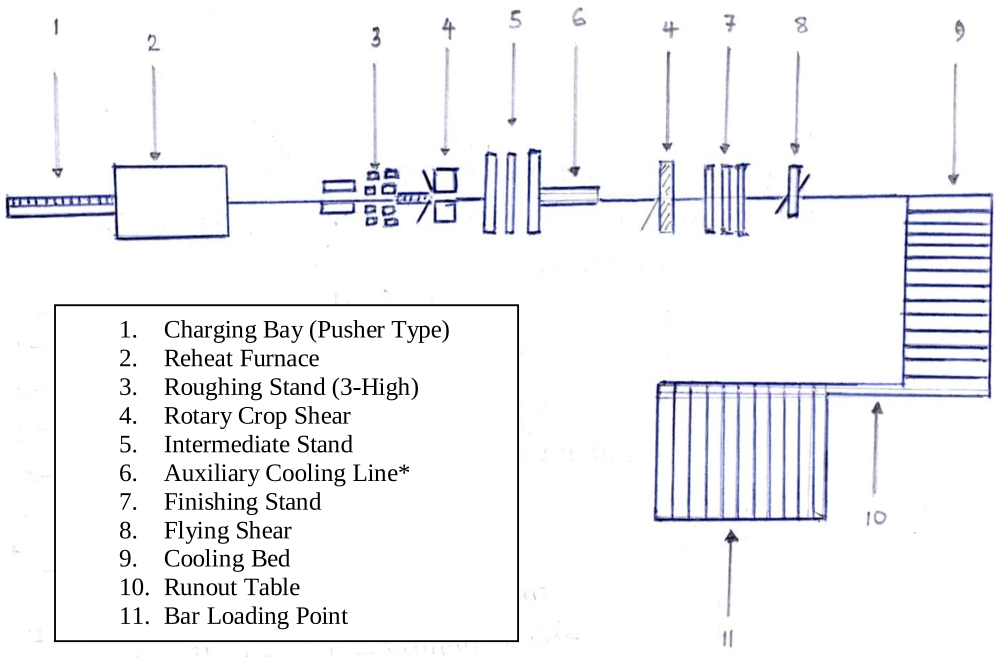

Figure 1. A conventional bar mill configuration.

finishing temperature from the conventional 1030 to 810˚C. Given that fine-grained product is usually desired, the best practice is to ensure a much lower working temperature at the last pass. This will drastically reduce grain growth during cooling. In this study attempt is made to obtain thermal variations data through monitoring of a conventional mill operation and evaluate its effect on the strength characteristics of the bars taking cognizance of the rolling stock chemistry.

EXPERIMENTAL PROCEDURE

Materials

Billets (100 x 100 x 1600 mm) of chemical composition as shown in Table 1 were charged into the re-heat furnace and heated to the rolling temperatures in the range 1200 – 1220°C. They were then rolled into 12 mm diameter high-yield bars. One hundred and twenty billets were rolled in each of the seven rolling cycles monitored.

Temperature tracking (TT)

Using a Jenway digital pyrometer model 220k, monitoring of the process temperature was carried out at each of the critical points where high temperature deformation occured namely roughing, intermediate and finishing stands respectively. As illustrated in Figure 1, the points at which temperature readings were obtained include the reheat furnace, roughing, intermediate and finishing stands respectively and at the cooling bed. Bar samples of 12 mm were obtained at the end of each rolling cycle for mechanical and microstructural analyses.

Mechanical property tests

In carrying out both hardness and tensile evaluation properties on the bars, the entire test specimens were prepared according to the

Table 2. Temperature tracking data (TTD).

Rolling cycle	Reheat oven to (°C)	Temperature at the stands (°C)			Cooling bed to (°C)
		Roughing, T_r	Intermediate, T_i	Finishing, T_f	
A	1217	1085	1013	872	792
B	1215	1075	998	848	762
C	1218	1094	1026	893	817
D	1209	1074	1005	864	786
E	1215	1078	1003	858	774
F	1216	1087	1016	879	800
G	1214	1076	1000	853	768

Table 3. Hardness of bars produced by conventional rolling.

Sample ID	Finishing temperature (˚C)	Hardness (HRB)	Carbon (%)
A	872	72.7	0.194
B	848	84.3	0.220
C	893	62.1	0.164
D	864	93.2	0.308
E	858	87.1	0.211
F	879	67.8	0.172
G	853	86.4	0.231

British standard (BS 18). Relevant clauses of the Nigerian Industrial Standards (NIS 117-42/50HD 2004) were also complied with. The test specimens hardness values were evaluated using the 'B' scale Rockwell hardness machine model United TB-II. An Instron electro-mechanical testing system model 3369 was used to obtain the test specimens yield and tensile strength characteristics.

Microstructural analysis

Test specimens were ground on a water-lubricated grinding machine using silicon carbide abrasive papers grades 240, 320, 400 and 600 grits. Final polishing of the specimens was effected with 0.5 µm chromic oxide powder. The surfaces so obtained were etched in 2% Nital solution and left for 30 s then, rinsed with water. The microstructural features of the specimens were examined under a metallurgical inverter microscope model FEROX PL at ×100 magnification.

RESULTS AND DISCUSSION

Results of the temperature tracking experiment are shown in Table 2 while listed in Table 3 are values of micro-hardness induced in the steel bars after air-cooling. Using the data obtained during tensile test on specimens, relevant tensile data are computed and presented in Table 4. The microstructural features of test specimens are shown on Figure 2 (a-g) Variations in the functional mechanical characteristics in terms of ultimate tensile strength, yield strength and hardness exhibited by test specimens in relation to the finishing temperatures are illustrated in Figures 3 and 4. The results of yield property behaviour with variation in carbon content are shown in Figures 5 and 6.

Figure 3 shows the variation of reheat temperatures of billets used during the rolling cycles. The values were almost the same, 1216± 2°C. The finishing temperatures, T_f however, vary widely and in the range 848.2°C to 893.4˚C.This gives a variation of 45.2°C, which is high enough to induce microstructural transformations during the air-cooling of the bars.

Wide variations in finishing temperatures can be attributed to the combination of two factors namely, in-process cooling and speed of rolling. The combination of direct and indirect cooling of rolling stock along with other heat sensitive devices of the mill facility impact on the finishing temperature. Other than technology, internal state of the rolling stock (British Standards Specification: (BS 4449 (1988); Curtin and Dewald, 2005) in term of cleanness affects the extent of strain hardening suffered during rolling hence, the speed of rolling. Similarly, large amount of strain hardening occasioned by inclusions usually give rise to delay in material flow (Curtin and Dewald, 2005).

The duration of rolling cycle in this study was in the range of 90-105 seconds culminating in different finishing temperatures. Generally, property sensitive parameters of hot rolled steel bars depend largely on the finishing temperatures (Choi, 2002). Similarly, flow stress; strain, strain rate and recrystallisation (static and dynamic) are influenced by temperature during hot rolling. However, temperature prediction is more important during finishing

Table 4. Calculated true stress and true strain.

A: Lo=23.14, A=19.46 mm^2		B: Lo=23.53, A=20.11 mm^2		C: Lo=23.36, A=19.32 mm^2		D: Lo=26.21, A=20.67 mm^2		E: Lo=23.37, A=20.19 mm^2		F: Lo=24.92, A=21.73 mm^2		G: Lo=22.38, A=19.71 mm^2	
True stress (MPa)	**True strain (ε)**	**True stress (MPa)**	**True strain (ε)**	**True stress (MPa)**	**True strain (ε)**	**True stress (MPa)**	**True strain (ε)**	**True stress (MPa)**	**True strain, (ε)**	**True stress (MPa)**	**True strain (ε)**	**True stress (MPa)**	**True strain (ε)**
210.7	0.02	256.6	0.03	56.0	0.01	179.8	0.02	101.0	0.01	99.0	0.01	157.4	0.01
266.8	0.03	336.1	0.04	107.2	0.01	225.8	0.03	153.1	0.02	189.2	0.02	260.8	0.02
321.8	0.04	366.6	0.05	158.9	0.02	296.4	0.04	256.1	0.03	285.3	0.03	315.1	0.03
379.4	0.05	444.9	0.06	215.3	0.02	354.1	0.05	339.5	0.04	336.0	0.04	367.4	0.03
448.1	0.09	488.3	0.09	267.1	0.03	435.9	0.06	417.6	0.05	414.7	0.08	442.2	0.04
518.0	0.11	585.0	0.12	323.5	0.04	500.5	0.07	482.1	0.09	498.4	0.11	499.2	0.05
535.4	0.12	634.5	0.15	396.1	0.06	559.8	0.10	586.0	0.12	553.6	0.15	553.6	0.09
586.8	0.16	652.2	0.16	507.1	0.12	672.9	0.12	651.3	0.16	591.5	0.18	648.4	0.12
614.3	0.19	692.6	0.19	604.6	0.22	748.8	0.16	696.1	0.20	623.0	0.22	749.6	0.20
618.8	0.20	712.1	0.22	616.7	0.25	801.5	0.20	711.4	0.23	635.5	0.25	773.2	0.24
596.4	0.23	728.2	0.25	588.3	0.28	806.9	0.21	680.6	0.26	645.7	0.28	745.8	0.27
531.5	0.25	607.5	0.30	480.1	0.30	676.2	0.27	563.3	0.29	484.9	0.35	624.6	0.30
298.0	0.25	361.8	0.30	268.9	0.31	381.9	0.28	328.1	0.29	290.8	0.35	344.5	0.30

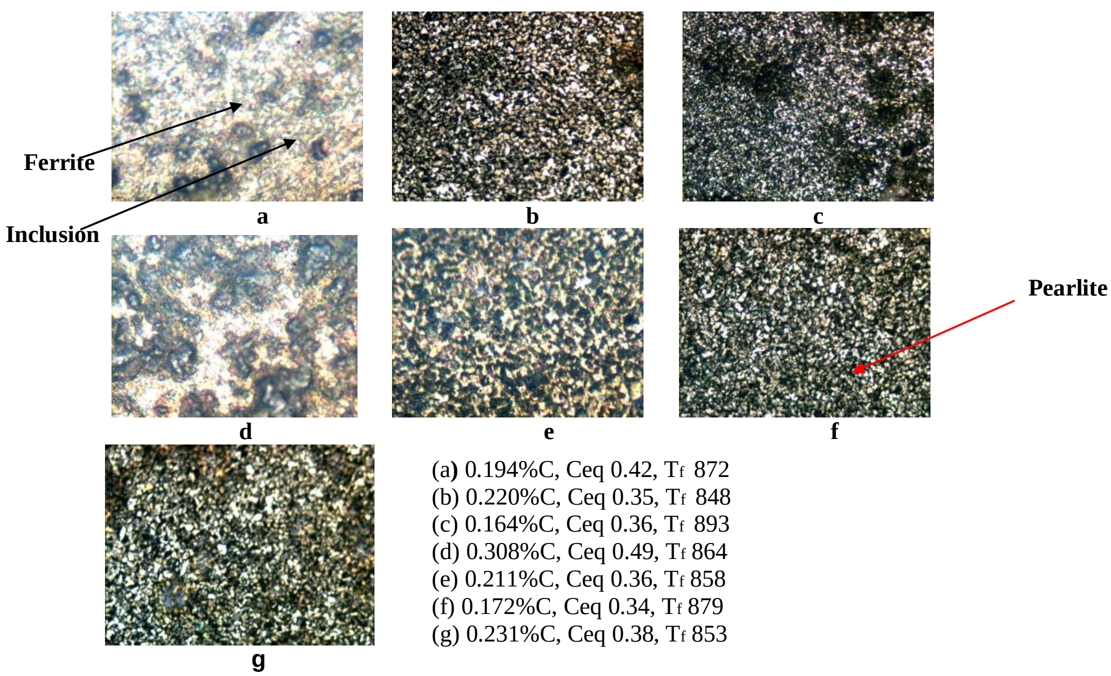

Figure 2. Micrographs of air-cooled rolled bar samples.

than roughing (Laasraoui and Jonas, 2007).

Microstructural observation

The micrographs on plates A-G showed two major phases, ferrite and pearlite including large pod-like non-metallic inclusions. The phases are distributed approximately in the ratio 0.3, 0.6 and 0.1 volume fractions respectively. Accurate prediction of microstructural evolution (Singh, 2007) in various carbon steels during hot rolling is one of the challenges steel millers are grappling with. This is because the finishing temperature is closely related to visco-plastic flow of the

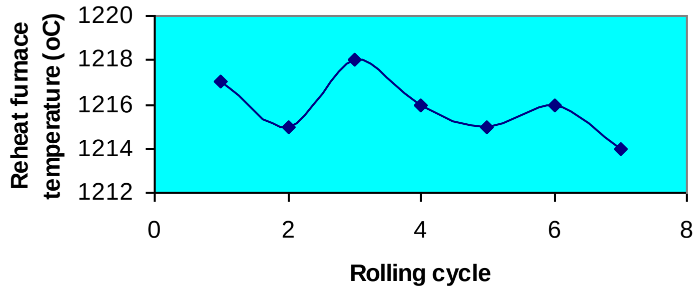

Figure 3. Variation of reheating temperature of rolling stock.

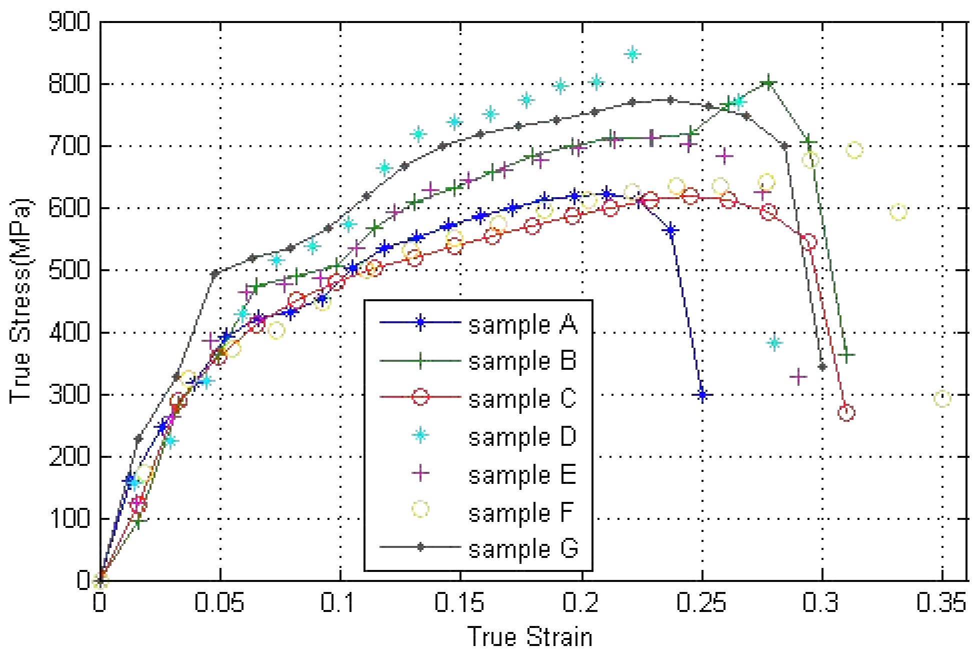

Figure 4. True stress against true strain.

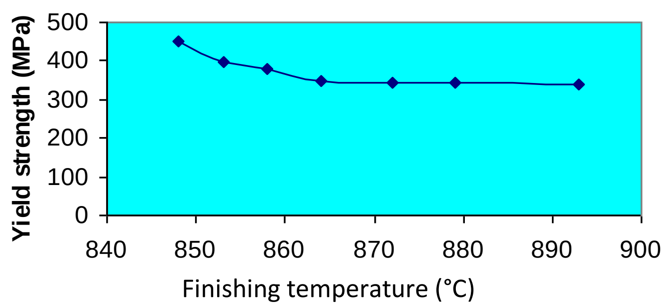

Figure 5. Yield strength against finishing temperature.

rolling stock, which affects the austenite grain size. Prior austenite grain size determines to a large extent the size of grain in the final product and hence its mechanical properties.

The rolling cycles monitored in this study had their finishing temperatures between 864 and 893.4°C, which is about 150°C above the lower critical point, 721°C. Hence, about 14 s elapsed before the start of

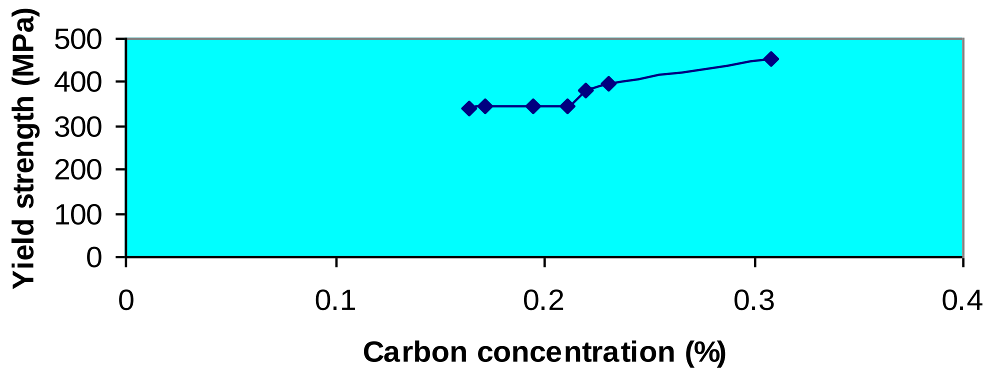

Figure 6. Variations of yield property with carbon concentration.

transformation. The delay resulted in the formation of coarse pearlite in test specimens at finishing temperatures of 872, 893 and 879°C respectively (Figure 2a, c, f).

However, the degree of coarseness of the pearlite reduces with decreasing finishing temperatures (Figure 2(e) T_f 858°C, (g) T_f 853°C and (b) T_f 848˚C). Coarse pearlite formed at the nose of TTT curve just below A_1 line exhibits high strength but poor ductility (Singh, 2007). This accounts for the low yield stress exhibited by all test specimens except specimen G (452.8MPa) as shown in Figures 5 and 6.

Ultimate tensile strength

The effects of microstructures in concert with other relevant parameters such as temperature, composition and cooling regime manifested in the flow curves of Figure 4. Specimen D exhibited the highest UTS, 806.9 MPa (Figure 4) mainly due to its relatively high carbon concentration, 0.30% coupled with high concentrations of inclusions (Ceq 0.49), which coalesced along with pearlite grains. This type of structure impedes dislocation mobility thereby requiring higher stress to cause plastic deformation. However, the bar is not recommended for application as reinforcement due to its abysmally low modulus of elasticity, 13493.6 MPa.

The non-metallic inclusions observed are a combination of tramp elements and slag that could not be removed at the refining stage of the steel from which the rolling stock was produced. Melting of most inclusions is not feasible during the reheating of rolling stocks in the furnace, which operates around 1200°C. This is because basic slags that are mainly compounds of silica and magnesia are highly refractory (Obikwelu, 1987). Such inclusions merely deform along the direction of rolling thus conferring directional properties on the rolled bars. Deformability of inclusions during hot working of steel influences the final properties of the product (Lai, 2007). Deformed inclusions also distort normal grain boundary arrangements that are potential barriers to dislocations motion.

Specimen G exhibited a good combination of UTS, 773.2 MPa and elastic modulus, 19157.9 MPa being the highest amongst all specimens tested. This may be attributed to two factors namely fairly low finishing temperature 855˚C, which gave rise to fine grained pearlite under air-cooling and low concentrations of inclusions, Ceq 0.38. The combination of these factors favours modest strain hardening both during elastic and plastic deformations.

Yield strength

Figure 5 shows the variations of test specimens yield strength at different finishing temperatures. Specimens A-F exhibited low yield strengths in the range 380.8 to 396 MPa. The yield strength of sample G, 452.8 MPa is comparable to local and international specifications, which are 420 MPa (NIS), 460 MPa (BS) and 500 MPa (ASTM).

The yield point phenomenon common in steel, aluminium and copper, is associated with small amounts of interstitial or substitutional impurities (Curtin and Dewald, 2005). This partly accounts for the observed substantial ductility in low carbon steels having interstitial carbon concentrations between 0.1 and 0.25%maximum. It has been shown (Lai, 2007; Maunder and Charles 2006; 1968) that almost complete removal of carbon and nitrogen from low carbon steel by wet-hydrogen treatment will remove the yield point phenomenon. However, only about 0.001% of either of these elements is required for a reappearance of the yield point.

Gradual increase in yield strength of test specimens occurred from 0.15 – 0.19% carbon (Figure 6). However, sharp increase in yield strength was observed between 0.19 and 0.23% carbon with corresponding finishing temperature in the range 848 to 858°C. Above this temperature range (Figure 5) and irrespective of the carbon composition, the yield strength dropped drastically. From this observation, it can be inferred that the type of microstructure developed at finishing

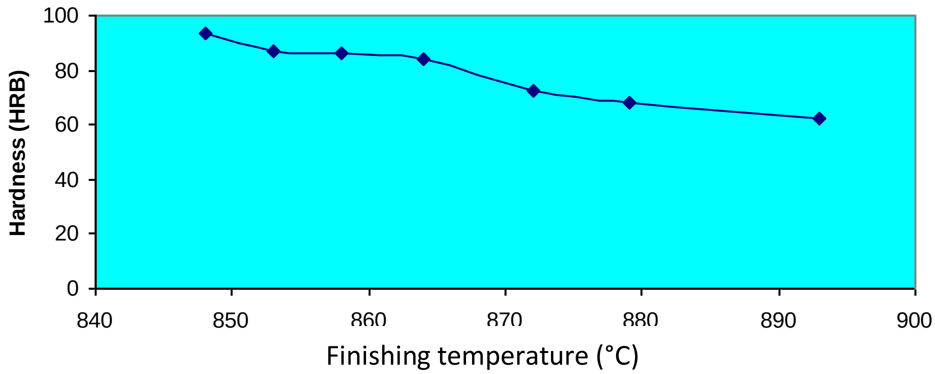

Figure 7. Variations of micro-hardness with finishing temperature.

temperatures greatly influenced the yield values obtained. Though specimen D has 0.30% carbon yet, it exhibited merely yield strength of 344.8 MPa. Yielding phenomenon in low carbon steel peaked between 0.20 and 0.30% of carbon. Beyond this range, the ductility of carbon steel is impaired. Apart from weldability criterion, this may be another basis for the BS 4449 specification of 0.25% carbon maximum in billets/ingots employed in hot rolling of construction steel bars.

Hardness of conventional rolled bars

Hardness exhibited by the specimens varies with the rolling stock carbon concentrations (Figure 7). Under natural air-cooling as the case in this study and at such finishing temperature range 848 to 893°C, the hardness measured must have been induced entirely by cementite rather than martensite. This is because martensite could not have formed given the prevailing processing conditions. Relevance of adequate surface hardness required in reinforcing bars concerns the ribs, which are meant to offer resistance to slip of the bar member within the structure. Free slip of bars should not be greater than 0.2 mm in a pull-out test (British Standards Specification: (BS 4449 (1988). The ribs must therefore exhibit sufficient bond strength in order to function effectively.

Conclusion

The influence of process factor such as finishing temperature, on the mechanical properties of hot rolled steel bar in a conventional mill has been investigated. From the analyses of results obtained, it can be concluded that in hot rolling the type and extent of in-process cooling method and duration of each rolling cycle largely determine the finishing temperature. Given that under conventional rolling whereby the bars are air-cooled, it is imperative that finishing temperature be just above A1 point in order to avoid the formation of coarse pearlite.

Finishing temperatures in the range 840 to 860˚C gave rise to fine grain microstructures that resulted in improved strength. Close monitoring of inter stand temperature will furnish prompt information regarding the extent of cooling required. This will ensure that rolled products get to cooling bed with temperature profile amenable to desirable microstructural evolution under air-cooling. Similarly, the rolling stock chemistry and soundness in term of level of cleanness exhibits a complementary influence on the strength characteristics of the steel bar.

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