Effect of Weight per Meter of Reinforced Bar on Mechanical Properties and Microstructure

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***Abstract*—Reinforced bars (rebars) are thermomechanically treated (TMT) bars that are hot-rolled from steel billets produced from scrap melted in an electric arc furnace at a temperature of about 1,600 ℃ (usually 1,580 ℃). The weight per meter of low-carbon steel rebars is one aspect that has been neglected by some steel producers during the tensile testing in rod mills. Determination of the weight per meter is explicitly required for a TMT rebar. Any reduction in mass will mean a lowering in the capacity of the steel reinforcing bar. A series of "heat" numbers or batches of molten steel from an electric arc furnace for the production of Steel Sample A (Y10 and Y12 rebars) were observed at a steel plant to investigate the effect of the weight per meter of a reinforced bar on the mechanical properties and microstructure. The rolling speed range was 3–14 m/s for different "heat values." Two other steel samples, B and C, were sourced from the local market to compare with Sample A. Samples collected from different sources from the local market, however, showed lower values of weight per meter, different from the prescribed standards. This affected not only the ultimate tensile strengths (UTSs) that were higher than normal, but also the microstructure that deviated from the standard for this material. Sample A showed not only a good combination of tensile strength and yield stress (YS) of 450 MPa and a maximum tensile strength of 650 MPa, but also a standard pearlite–ferrite microstructure, whereas Samples B and C exhibited excessively high strengths and brittle behavior and were prone to failure.**

***Index Terms*—Billets, hot rolling, microstructure, rebar, recrystallization.**

I. Introduction

Thermomechanical treatment is one route used to control and produce quality steel bars. Upon completion of the rolling process, the rebar in the austenitic state enters a water box where the surface is superficially cooled down by water at an adequate pressure and flow rate to decrease the temperature of the surface layer below the martensite start temperature. The dwell time for this quenching process is less than one second. This results in rapid cooling of the surface area of the rebar, while the inside or core of the rebar remains red-heated at this stage. A water flow rate in the range of 600–800 m^3/h is introduced, depending on the diameter of the bar being processed, at a pressure in the order of 1.2 MPa [1]. At the cooling bed, the quenched rebar is exposed to air cooling, where the surface gets autotempered because of the heat flow from the red-hot core to the low surface temperature. Finally, the austenitic core transforms into ferrite and pearlite.

During hot rolling, events such as work hardening, dynamic recovery, and dynamic recrystallization (DRX) are responsible for the microstructural changes that take place during the deformation [2]. During transformation of austenite to ferrite, grain refinement due to recrystallization is important. The interrelation of recrystallization, recovery, grain growth, precipitation, and transformation, among others, leads to the development of the microstructure through thermomechanical treatment [3].

Small microalloying additions of carbonitride-forming elements, such as niobium, vanadium, and titanium, can increase the strength of low-carbon and low-alloy steels. The main role of these minor alloying additions is to form fine dispersions of carbonitrides, which (1) can control the austenite grain size outside the solution during austenitization and (2) can precipitate in both austenite and ferrite during cooling from the solution treatment temperature. Controlling these precipitation processes during the thermomechanical treatment of steel products can bring about high strength levels while maintaining acceptable ductility.

As a semifinished product, the microstructure of the billet before rolling is initially composed of coarse grains of austenite. The austenite grain structure begins to change when the billet passes through the rollers and becomes compressed. During this stage, the austenite grains are elongated into a pancaked structure, and each grain experiences a change in dimension, usually with deformation bands induced within the grains (Fig. 1) [4, 5].

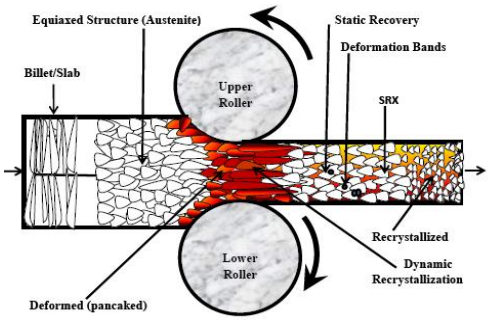

Figure 1. Recrystallization during hot rolling (adapted from Figure 1.8 of [5]).

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Recrystallization can be considered as one of the most powerful tools for achieving significant grain size refinement during hot working. When this process occurs during deformation, it is referred to as DRX, whereas the term "static" is applied when it occurs after deformation [3]. During hot rolling, each pass is characterized by the strain applied, the rate at which strain is applied, the temperature, and the interpass time. These process parameters, together with material characteristics such as chemical composition and initial grain size, have an influence on the kinetics of recrystallization and the formed grain size.

There are two practical aspects of DRX that need to be considered: the critical strain (ε_c) necessary for the start of DRX and the resulting recrystallized grain size. The critical strain ε_c has been associated with the peak strain ε_p, a parameter that is easier to measure experimentally than ε_c. The relationship between ε_c and ε_p has the form $\varepsilon_c = k\,\varepsilon_p$, where k is a constant, whose reported values range from 0.5 to 0.87. These values are dependent on the steel's chemical composition. The peak strain is determined by the initial austenite grain size D_0 and the Zener–Hollomon parameter Z, as indicated in Eqs. (1) and (2) [3].

$$\varepsilon_p = A \cdot D_0^m \cdot Z^p, \tag{1}$$

$$Z = \dot{\varepsilon}\exp\left(\frac{Q_{\mathrm{def}}}{RT}\right). \tag{2}$$

In Eq. (2), $\dot{\varepsilon}$ is the strain rate, Q_{def} is the apparent energy of activation for deformation, R is the gas constant whose value is 8.31 J/K mol, and T is the absolute temperature. The energy of activation Q_{def} and the coefficients of the equations (A, m, and p) are dependent on the material.

Softening of the austenite under hot working conditions can occur after deformation during the interpass intervals. Since recovery in austenite is very limited, recrystallization is the main softening mechanism [3]. Under conditions where DRX has not been activated ($\varepsilon < \varepsilon_c$), the recrystallization that can occur in the interpass time is called "static recrystallization" (SRX). The evolution of the recrystallized fraction with time is represented in Eq. (3) as articulated by Avrami [3]:

$$X = 1 - \exp\left(-\ln 2 \cdot \left(\frac{t}{t_{0.5x}}\right)^n\right). \tag{3}$$

In Eq. (3), X is the recrystallized fraction after time t, $t_{0.5x}$ is the time required to reach 50% recrystallization, and n is Avrami's exponent. In the case of SRX, the value of the exponent n ranges between 1 and 2 [3]. The nucleation and growth of new grains in the deformed austenite microstructure are the basic requirement for SRX. A general expression that takes into account the parameters that affect the value of $t_{0.5}$, for the case of SRX, is shown in [3, 6]

$$t_{0.5\mathrm{srx}} = A\varepsilon^{-p}\dot{\varepsilon}^{-q}D_0^m \exp\left(\frac{Q_{\mathrm{srx}}}{RT}\right) \tag{4}$$

where m, p, and q are constants and Q_{srx} is the activation energy for SRX.

II. Experimental Procedures

A. Materials as Received Steel Samples

The materials used in this experiment were locally produced rebars from three different companies. Steel Sample A was directly produced by a steel plant, and the other two samples, B and C, were sourced from the local market.

B. Methodology

The rebar diameters used in this study were Y10 mm and Y12 mm, respectively. The chemical composition of Sample A was established using an Optical Emission Spectrometer. The compositions of Samples B and C were, however, not established, but they were weighed using the Adams scale and subjected to tensile and bending tests. Three samples from each rebar size were selected and 18 samples were investigated. The standard guide used to prepare the samples for observation in microscopy was ASTM E3-11. The samples were mirror-polished and etched using 2% Nital. The etching time was in the range of 15–20 s, and samples were then viewed using optical microscopy to identify the grain structure.

C. Chemical Composition

The alloying elements of rebars comprised (wt.%) 0.24 C, 0.44 Mn, 0.08 Si, 0.020 S, 0.035 P, 0.23 Cr, 0.12 Ni, 0.02 Mo, 0.30 Cu, and 0.079 V. The carbon equivalent (CE) of the alloying elements was obtained using [7]

$$\begin{aligned}\%\,\mathrm{CE} &= \mathrm{C} + \frac{\mathrm{Mn}}{6} + \frac{\mathrm{Cr}+\mathrm{Mo}+\mathrm{V}}{5} \\ &\quad + \frac{\mathrm{Ni}+\mathrm{Cu}}{15} \\ &\approx 0.44\%.\end{aligned} \tag{5}$$

0.44% is an average value of CE, which was expected and is within the threshold values required by the South African Bureau of Standards (SABS: SANS 920:2011) and Zambia Bureau of Standards (ZABS: ZS 433:2005), respectively. The maximum %CE according to these standards is 0.51%.

D. Tensile and Bending Tests.

Samples were subjected to tensile and bending tests using a computerized 60-metric-ton TUE-C-600 Universal Testing Machine. The ASTM E-290 standard was used to conduct the bending test. This standard requires that the testing be done primarily to assess the extent of ductility in the material. Other conditions for this standard are that the bending and rebending specimens should have no cracks or any open defects after the visual inspection of the curved surface [8].

III. Data Collected and Results

A. Collected Data

The data collected for the weight per meter and tensile test values are shown in Tables I and II for Y10 mm and Y12 mm rebars. Table III shows the SABS (SANS 920:2011) and ZABS (ZS 433:2005) for reference on weight-per-meter requirements.

B. Results

Graphical illustrations of the relationship between the weight per meter of a rebar and the mechanical properties for Y10 mm and Y12 mm are shown in Fig. 2 and Fig. 3, respectively, and discussed in Section IV.

TABLE I. Tensile test report (to rod mill), Y10 mm.

Steel	Wt./m (kg/m)	YS (MPa)	UTS (MPa)	%El
A1	0.5793	477.27	553.70	38.00
A2	0.5764	506.60	638.15	34.00
A3	0.5806	508.60	632.71	28.00
B1	0.4723	587.58	783.45	28.00
B2	0.4514	575.62	790.61	26.70
B3	0.4872	598.16	804.52	25.12
C1	0.4218	615.04	826.47	21.20
C2	0.3984	596.60	872.10	19.32
C3	0.4410	581.38	857.26	20.71

TABLE II. Tensile test report (to rod mill), Y12 mm

Steel	Wt./m (kg/m)	YS (MPa)	UTS (MPa)	%El
A1	0.8683	456.71	571.16	26.70
A2	0.8638	478.21	545.82	25.00
A3	0.8646	444.52	536.58	30.00
B1	0.8158	528.86	659.34	31.96
B2	0.8195	566.10	709.20	26.67
B3	0.8232	544.15	694.63	30.00
C1	0.8080	557.26	820.15	25.00
C2	0.8172	506.03	803.42	16.67
C3	0.8198	541.21	767.00	23.33

TABLE III. STANDARDS SANS 920:2011 AND ZS 433:2005.

Steel size	Wt./m (kg/m)	YS (MPa)	UTS (MPa)	%El
Standard (Y10 mm)	0.617 (±6%)	450 min.	650 max.	14% min.
Y10	0.619	524	621	22
Standard (Y12 mm)	0.888 (±4%)	450 min.	650 max.	14% min.
Y12	0.885	506	612	24
Standard (Y16 mm)	1.58 (±4%)	450 min.	650 max.	14% min.
Y16	1.56	495	584	22

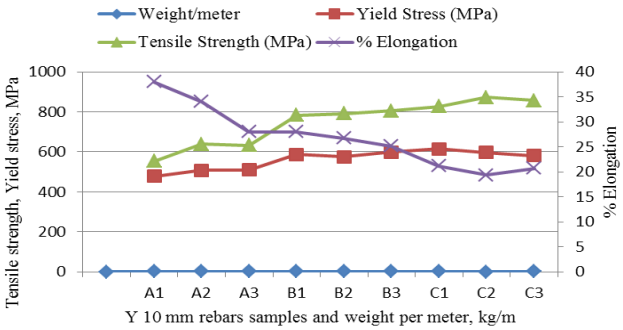

Figure 2. Weight per meter and mechanical properties for Y10 mm rebar.

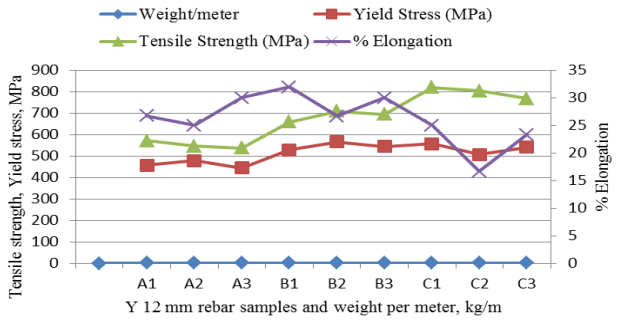

Figure 3. Weight per meter and mechanical properties for Y12 mm rebar.

C. Microstructural Investigation

The microstructures in transverse and longitudinal sections were examined at different positions in the samples in order to see the uniformity of the microstructure. Figure 4(a) shows a core microstructure dominated by pearlite colonies, as opposed to ferrite for Samples B and C. A well-developed ferrite and pearlite microstructure was also observed at the core of Steel Sample A, as shown in Fig. 4(b). Figures 5(a) and 5(b) are core micrographs taken at different positions, still showing a complete deviation of the expected pearlite–ferrite microstructure for Samples B and C. Figures 6(a)

and 6(b) are other optical micrographs showing the microstructure for the case area (martensite) and a core area of pearlite and ferrite taken at different positions in another steel sample (Sample A). These micrographs still show fully and well-developed microstructures.

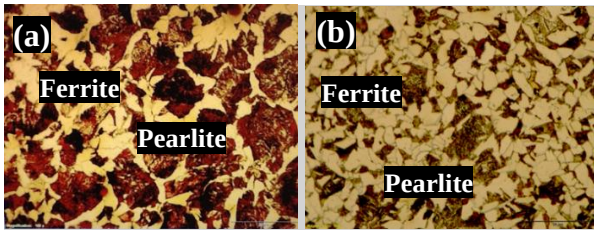

Figure 4. Optical micrographs for Steel Samples A, B, and C: (a) microstructure of Samples B and C and (b) microstructure of Sample A, all taken at 100 × magnification. Pearlite: dark; ferrite: light.

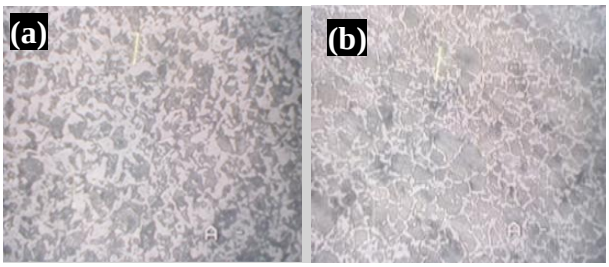

Figure 5. Optical micrographs for Steel Samples B and C, showing a complete deviation from fully and well-developed pearlite and ferrite structure, taken at 100x magnification. Pearlite: dark; ferrite: light (in both cases).

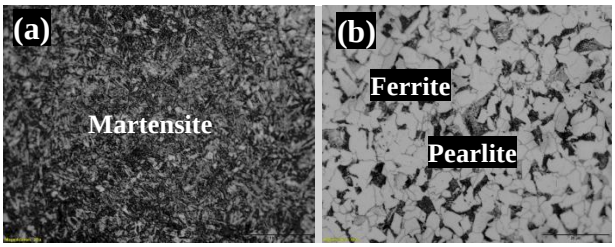

Figure 6. (a) Optical micrograph of a well-developed case area (martensite) of Sample A. (b) Core area of a well-developed pearlite–ferrite microstructure for Sample A, taken at 100x magnification. In (b), pearlite is dark and ferrite is light.

IV. Discussion

The tensile test reports compiled in Tables I and II together with the graphs shown in Figs. 2 and 3 clearly show that Samples B1, B2, B3, C1, C2, and C3 did not meet the weight per meter required, and their respective tensile strengths are far higher (in the range of 700–800 MPa) than the standard. The tensile tests conducted on Sample A showed that the yield stress (YS) and tensile stress were within acceptable limits (450–650 MPa), without much variation. Percentage elongation was seen to be reducing with the corresponding reduction in weight per meter for the Y10 rebar. The percentage elongation for the Y12 rebar was higher for a lower tensile strength and lower for a higher tensile strength, a trend typical of larger profiles. This can be attributed to the reduction of the cooling rate of the profile at the cooling bed.

The bending tests on the three samples revealed multiple surface cracks visible to the naked eye on Samples B and C, as shown in Fig. 7(a), and these caused the test to fail. Steel Sample A in Fig. 7(b), however, showed excellent results, with no indication of cracks on the surface. The bending test also indicated that Sample A was more ductile than the other two, which exhibited a brittle behavior and were liable to failure.

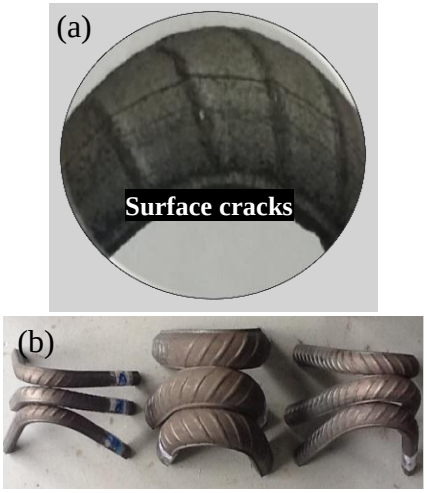

Figure 7. Bending test results: (a) multiple surface cracks visible to the naked eye on Samples B and C; (b) excellent results, with no indication of cracks on the surface.

V. Conclusions

This study has shown that the weight per meter is explicitly required when carrying out tensile tests in rod mills. During the heat treatment of thermomechanically treated (TMT) rebar, steel producers of this product must monitor the water's flow rate and dwell time during the quenching process, as these have an effect not only on the ultimate tensile strength (UTS), YS, and elongation, but also on the microstructure. These two variables (water flow rate and dwell time) are easy to control, yet very crucial to the production of high-quality rebars. It has also been observed that smaller profiles of rebars, such as Y10 mm rebars, tend to be harder and more brittle than larger profiles, so the dwell time for quenching and the water flow rate need to be controlled properly for this profile, especially that the surface area is small. Tables I and II clearly confirm that the weight per meter for Steel Sample A is within the prescribed threshold as per the standards shown in Table III. Steel Samples B and C, however, failed to meet the requirements given the thresholds. It was therefore deduced that the fundamental mechanical properties, namely, the UTS, YS, and elongation, of the rebar including the weight per meter are explicitly required for good-quality rebars.

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REFERENCES

[1] J. Madias, M. Wright, and P. Wolkowicz. Reinforcing Bar: Hardening Mechanisms and Performance in Use. Conference: AISTech 2016 proceedings. [Online], pp. 2287-2296. Available at: https://www.researchgate.net/publication/305221514_Reinforcing_Bar_Hardening_Mechanisms and_Performance_in_Use, [Accessed 17 May 2017].

[2] J. H. Beynon and C. M. Sellars, "Modelling microstructure and Its effects during multipass hot rolling," *ISIJ International*, vol. 32, no. 3, pp. 359-367, 1992.

[3] B. LÒPEZI and J. M. Rodriguez-IBABE, "Recrystallization and grain growth in hot working of steels," in Jianguo Lin, Daniel Balint and Maciaj Pietrzyk, ed, in *Microstructure Evolution in Metal Forming Process*, chapter 4, Woodhead Publishing Limited, Cambridge, 2012.

[4] R. A Grange, "Microstructural alterations in iron and steel during hot working," *Fundamentals of Deformation Processing*, Syracuse Univ. Press, Syracuse, New York, pp. 299-320, 1964.

[5] J. Ryu, *Model for Mechanical Properties of Hot-Rolled Steels*. Diss. Master Thesis, Pohang University of Science and Technology, Korea, 2008.

[6] C. M. Sellars, 'The physical metallurgy of hot working," in Sellars CM and Davies GJ (eds), *Hot Working and Forming Processes.* London: Metals Society, pp. 3-15, 1980.

[7] V. Musonda, E. T Akinlabi, and T. C Jen, "Effect of water flow rate on the yield strength of a reinforced bar," 2017.

[8] ASTM E 290-97A, 2006, "Standard test methods for bend testing of material for ductility," *ASTM International*, PA, USA. (www.astm.org).

Mr. Musonda was born in Mufulira, Copperbelt Province, Zambia. He completed his Bachelor of Engineering degree (B.Eng.) at the University of Zambia Great East Road Campus in Lusaka, Zambia, in 2003, specializing in mechanical engineering. He obtained his Master of Science degree (M.Eng.) in mechanical engineering in 2007 from the University of Cape Town in South Africa, specializing in digital shearography and infrared thermography as nondestructive testing (NDT) techniques for composite materials. Currently, he is a Special Research Fellow pursuing the Ph.D. degree at the University of Johannesburg in South Africa. The field of study in this Ph.D. is "Property Evolution of Hot Rolled Steel," with emphasis on the recrystallization kinetics for achieving grain size refinement during hot rolling. He has 15 years of experience in the air force as a Maintenance and Airworthiness Engineer (Aircraft Engines and Structures and Ground Support Equipment). During his tour of duty in the air force, he rose to be the Head of Technical Services until 2012 to join the University of Zambia as a Lecturer at the School of Engineering, Department of Mechanical Engineering. He also served as an Assistant Dean (Technical) at the University of Zambia for one year before commencing his Ph.D. studies.

Prof. Tien-Chien Jen joined the University of Johannesburg in August 2015 as a Full Professor at the Mechanical Engineering Science Department. Prof. Jen received his Ph.D. degree in mechanical and aerospace Engineering from the CLA. He has recently established the Joint Research Centre with Nanjing Tech University of China on the "Sustainable Materials and Manufacturing." Prof. Jen is also the Director of Manufacturing Research Centre of the University of Johannesburg. Meanwhile, the National Research Foundation of South Africa has awarded him an NNEP grant (National Nano Equipment Program) that is worth of one million USD to acquire two state-of-the-art atomic layer deposition (ALD) tools for ultrathin film coating. These two ALD tools will be the first in South Africa and possibly the first in the African continent. In 2011, Prof. Jen was elected as a Fellow of the American Society of Mechanical Engineers, which recognized his contributions to the field of thermal science and manufacturing. It was stated in the announcement of Prof. Jen's Fellow status in the 2011 International Mechanical Engineering and Congress Exposition that "Tien-Chien Jen has made extensive contributions to the field of mechanical engineering, specifically in the area of machining processes. Examples include, but not limited to, environmentally benign machining, atomic layer deposition, cold gas dynamics spraying, fuel cells and hydrogen technology, batteries, and material processing." Prof. Jen has written a total of 198 peer-reviewed articles, including 84 peer-reviewed journal papers, published in many prestigious journals. He has also written six chapters in a special topics book.