

Thermo-Mechanically Treated Bars Made from Recycled Steel in Uganda

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ABSTRACT

Thermo-mechanically treated (TMT) reinforcement bars constitute an important turning point in the construction industry due to their capacity to envelope high strength, high ductility and low cost simultaneously. The properties of any material depend heavily on their chemical content. Steel in Uganda being mainly of the recycled origin has an abundance of residual elements. The purpose of this study was to establish the effect of these elements on the quality of the locally made TMT recycled steel bars. Particular interest has been paid to features influencing hardenability since it is the underlying factor in the mechanical peculiarities of TMT bars. Micro-hardness plots, tensile tests and spectro-analysis have been done on thirty randomly selected samples from local steel manufactures in order to relate the mechanical properties of the bars to their tramp element content. Unequal axial distribution of properties, asymmetrical radial distribution of hardness, low and inconsistent ring to core hardness ratio have been sighted as direct results of the recycled origin of the bars. Ladle refinement and the use of sponge/HB iron have been recommended as viable solutions in view of the existing national ore resources.

Keywords: *Tramp elements; reinforcement bars; hardenability; ductility; recycled steel.*

1. INTRODUCTION

Thermo-mechanically treated (TMT) or quenched and tempered (Q&T) concrete reinforcement bars have been in use worldwide for the last forty years in preference to twisted bars mainly owing to their superior tensile and ductility properties. This has been in response to the increase in the demand for low cost re-enforcement steel bars with a maximum guaranteed yield point [14]. In Uganda, however, only small amounts of these bars used to be imported for selected jobs until the production of TMT bars was started several years ago. Currently, three of the seven steel plants in the country produce TMT bars even though their use is not yet as widely spread as the cheaper albeit less reliable, more historically accepted CTD bars.

The direct benefits of TMT bars to the customer are reduced total weight of re-enforcement bars per unit weight of concrete leading to reduced cost, reduced manpower for re-enforcement bar fabrication and lower transportation costs. This is achieved with bars of 500Mpa yield strength and above as opposed to the 415Mpa obtainable in cold twisted bars, saving up to 10% in steel consumption [19].

In the past such strength has been achieved by using higher carbon content and/or alloying elements [14]. Such bars were usually 0.3%-0.5%C and consequently had limited weldability; often vulnerable to hydrogen cracking. Cold worked bars (CTD) with up to 0.15%C were more weldable but lost their hardness beyond 300°C,

a temperature normally reached during welding and hot bending on site. Low carbon high strength weldable bars can be produced by alloying but only at large costs, making them uneconomical [1].

The superiority in weldability of TMT bars thus makes them an inevitable preference to any other mild steel reinforcement bars. The bars also have more consistent properties since they are produced by a continuous on line rather than batch type process as in the case of cold twisted deformed (CTD) bars. This is all in addition to the higher corrosion resistance due to the absence of residual stresses and the retention of the inert blue secondary oxide scale formed during hot rolling.

In their production, TMT reinforcement bars are hot rolled as usual and as they exit the last mill-stand, they are rapidly cooled (quenched). During this step, they undergo surface hardening by quenching in which the surface is converted into a martensitic layer. The core naturally remains hot and as soon as the cooling process is over, the surface layer is warmed by the residual heat from the core; thus self-tempering the surface into a martensite and bainite rim. The bars, now at uniform temperature, are then left to cool naturally in still air to ambient temperature (Fig.1). At this stage, the residual austenite is transformed to a refined, tough and ductile ferrite and pearlite core which determines the ductility of the bars [4]. All this is achieved without the addition of costly alloying elements and the consequent difficulty in heat treatment.

The ultimate strength, ductility and uniformity of the steel bars depends on the chemical composition constituted by the carbon and alloying (tramp) element content, quenching parameters such as water volume and pressure and the number of cooling elements which determine their ultimate equalization temperature and the final state of the martensitic layer [9].

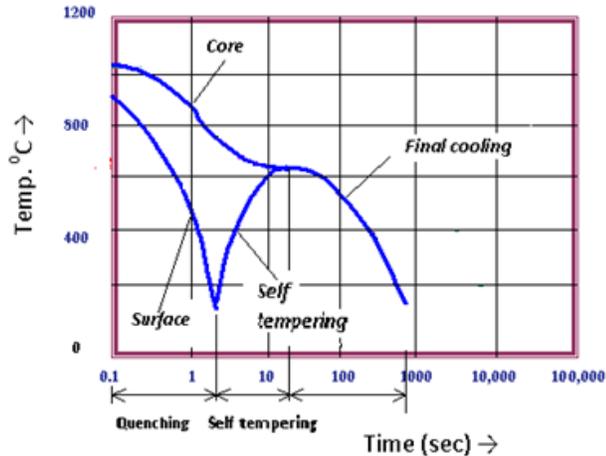


Fig. 1: TMT Cooling Process, after Markan, 2004

Martensite is a hard, brittle, unstable, body centered tetragonal (BCT) phase formed when face centered cubic (FCC) austenite is rapidly cooled (quenched), trapping carbon atoms that are not given time to diffuse out of the FCC austenite structure. Here stresses also originate due to the volume difference between austenite and martensite and are partly responsible for its inherent dislocations density. This high dislocation density in martensite is the underlying factor in its hard and brittle nature and the reason for its strength [10]. In order to endow steel with better toughness and reduce hardness, it must be tempered. During the tempering process, interstitial carbon atoms earlier trapped during quenching are able to diffuse throughout the martensite and segregate at dislocations and inter-crystalline boundaries, thus reducing resistance to slip [8]. In this way, tempering the TMT bars reduces hardness and since the retained heat effect is more at the core of the bars, the transformation of martensite to ferrite/pearlite is more at the core, creating a hardened martensitic rim and a soft, ferrite pearlite core. The combination of the core and rim properties produces a reinforcement bar with superior strength and ductility to that of CTD bars (Fig.2).

The area fraction of the martensite rim to the total cross section of the bars and the maximum hardness on quenching and tempering are directly dependent on the composition of the steel for while the former is a function of hardenability which depends on the alloy (tramp element) content, the latter is a function of the carbon content [3]. Elevated levels of tempered martensite

inevitably result in higher bar strength but at the expense of the overall bar ductility and are therefore watched carefully. For 550Mpa yield stress grade TMT bars for example, the martensite rim area fraction is limited to about 35% [15].

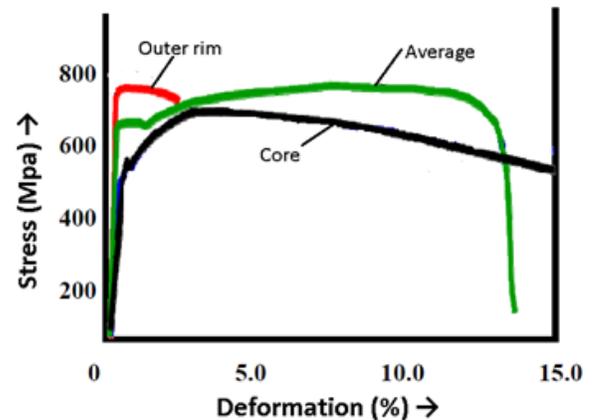


Fig.2: Stress Strain Diagrams for Various Phases in TMT Bars (Islam, 2010)

The strength, hardness and ductility (or brittleness) of the TMT are thus related to the chemical composition and ultimately to the phases present. In this study this relationship has been used to assess the variation of the associated properties both across the bar section and along the length of the bars with a view to quantifying the effect of tramp (residual) elements on the quality of the TMT bars in Uganda. The difficulty in controlling the composition of the steel often results in unpredictable properties of the TMT bars made thereof since the bar properties are determined by the hardenability which is the direct result of the alloy content.

2. MATERIALS AND METHODS

Thirty pieces of 32mm nominal diameter TMT reinforcement bars randomly selected from different points in the country were tested. Micro-hardness measurements of cross-sections were carried out from surface to core on all the pieces using an HR-500 Mitutoyo Rockwell hardness tester with a 120⁰ diamond cone indenter at 150kg load, reading at 1mm intervals. Tensile tests were carried out on the thirty pieces using Blue Star UTN- (E) 100 Universal Testing Machine in accordance to the EAS 412-1:2005 (ISO 6892). Four of the samples were selected on the strength of their representative results. Additional hardness readings were taken of the samples to determine the hardness pattern on both extremes of the bar samples. The chemical composition was determined using a Spectrol Lab. spark spectrometer and the carbon equivalents calculated according to equation 1.

$$C_{eq} = C + A(C) * \{Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Nb + V + Mo)/5 + 5B\} \quad (1)$$

where:

$$A(C) = 0.75 + 0.25 \tanh\{20(C - 0.12)\}$$

Bend tests were conducted in accordance with East African standard, EAS 412-2-2008, using $\Phi 200\text{mm}$ mandrel.

3. RESULTS

The comparison of maximum and minimum hardness between extreme ends A and B of the bars and the minimum and maximum hardness values across the sections of the bars are shown in Table 1. The maximum hardness corresponding to the martensite ring stands out clearly while the demonstrably softer ferrite/pearlite forms the core in each case giving the bars their characteristic resilience.

Four outstanding micro-hardness plots are shown graphically in Fig.3. Their average chemical compositions and carbon equivalents are as in table 2.

Samples R16, R21, R23, R25 and R26 exhibited almost ideal micro-hardness distribution. Micro-hardness plot for R16 is shown in Fig.3. The ratio of outer ring to core hardness for this group ranged between 8.6 and 10.4. The samples R4, R13, R22 and R27 showed very low ratios ranging between 1.4 and 1.7 although their maximum hardness was comparable with that of the other samples which fell between HRc. 30.5 and 24. The twenty-one other samples examined showed intermediate maximum hardness values.

The micro-hardness distribution across R1, R7, R9, R16, R24 and R28 showed evidence of asymmetry on at least one of the ends in each case. Of these, R7, R16 are shown in Fig.3.

The corresponding ultimate strengths of the bars lay between 512 and 690 Mpa except for samples R1, R7, R11, R16, R17, R22, and R27 whose ultimate strength values were respectively: 712, 708, 701, 724, 710, 754 and 709 Mpa. The ultimate to yield strengths ratios (σ_u/σ_y) for the samples lay between 1.10 and 1.25 except for R1, R9, R16, R22, and R27 whose values were between 1.07 and 1.10, well in conformity with EAS 412-2-2005.

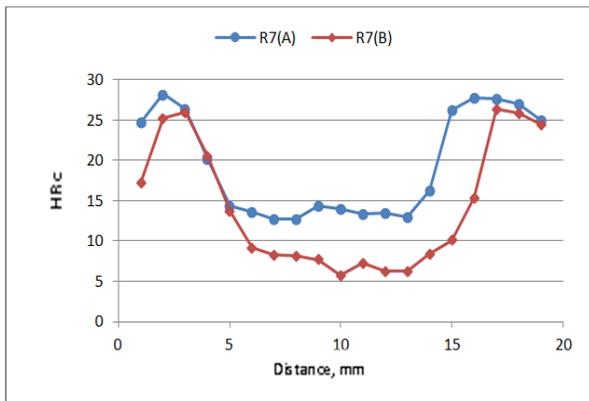
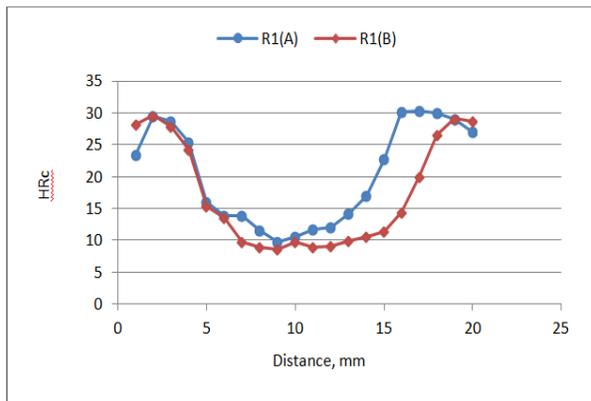
All the thirty samples yielded acceptable bend test results.

Table 1: Comparative Hardness Values (HRc)

Sample	Min	Max	Max/Min
R1(A)	9.8	30.2	3.1
R1(B)	8.6	29.6	3.4
R7(A)	12.7	28.2	2.2
R7(B)	5.7	26.4	4.6
R16(A)	2.4	25.0	10.4
R16(B)	2.8	24.0	8.6
R22(A)	18.0	30.5	1.7
R22(B)	18.5	26.5	1.4
R27(A)	19.2	28.9	1.5
R27(B)	17.2	28.0	1.6

Table 2: Average Composition of Bars

S'ple	C	Cu	Mn	Cr	Ni	Si	Ti	Mo	Nb	B	V	C _{eq}
R1	0.207	0.04	0.60	0.07	0.126	0.247	0.001	0.008	0.001	0.0009	0.009	0.35
R7A	0.197	0.04	0.60	0.07	0.128	0.245	0.001	0.008	0.001	0.0009	0.009	0.34
R7B	0.191	0.04	0.42	0.07	0.125	0.144	0.001	0.008	0.001	0.0006	0.009	0.29
R16	0.195	0.11	0.60	0.05	0.043	0.271	0.001	0.014	0.001	0.0010	0.003	0.33
R22	0.202	0.13	1.15	0.06	0.061	0.409	0.001	0.025	0.001	0.0014	0.004	0.44



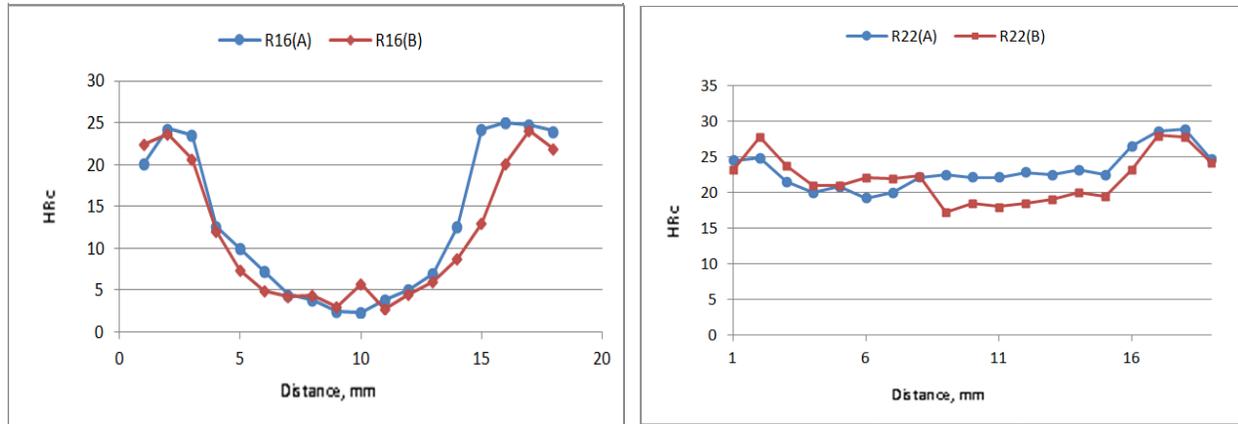


Figure 3. Micro-Hardness Plot R1,R7,R16, R22

4. DISCUSSION

Prior to the making of TMT bars, the composition of the steel is determined and the optimum cooling conditions set to guarantee that the maximum temperature attained at the surface of the bar after quenching (the equalization temperature), which will be the tempering temperature for that composition, gives a resulting steel bar with the correct ratios of volume and hardness of the tempered outer ring to the pearlite/ferrite core [11]. These cooling conditions include the final billet rolling temperature which represents the quenching temperature, spray intensity and billet speed at the final roll [1].

The fact that samples R16, R21, R23, R25 and R26 have almost ideal micro-hardness distribution with moderate composition in terms of carbon, manganese and other elements leading to equally moderate carbon equivalent values as exemplified by R16 in Fig. 3, Table 1 and 2. This therefore shows that the equalization temperature corresponded with that required for the respective steel compositions.

That the micro-hardness readings of R4, R13 and R22 on both sides of the bars, however, showed very low outer

$$HB = 2.84H_h + 75(\%C) - 0.75(\%Si) + 14.25(\%Mn) + 14.77(\%Cr) + 128.22(\%Mo) - 54(\%V) - 0.55(T_f) + 435.66 \quad (2)$$

where HB is the hardness after hardening and tempering, H_h the hardness after quenching and T_f the hardening temperature.

The tramp element content uplifts the steel carbon equivalent so that the steel hardenability (critical diameter) which gave rise to more martensite at the core would have required a higher equalization temperature than the one set for the average composition of the steel in order to give the conversion of the carbides time to dissolve and facilitate the conversion of martensite to softer, more ductile pearlite to facilitate the formation of the combination of hardness at the surface and toughness

ring to core hardness ratio as demonstrated by the micro-hardness plot for R22 in Fig.3 and the maximum to minimum hardness in Table 1 is a symptom of low equalization temperature which resulted from the steel from one part of the teeming ladle having had a different composition from the average one determined prior to the setting of the spray nozzles. This is known to happen as a result of the difference in composition of the different scrap types melted in the induction furnace, leading of unequal composition of the final melt. Lack of stirring action at the teeming ladle stage makes one part of the melt to have both different composition and temperature from the other parts [12]. The composition of R22 in Table 2 was only slightly high carbon content but had a relatively elevated manganese and silicon content with an accompanying high carbon equivalent (0.44). The hardness obtained after tempering (tempered martensite) is a linear function of the original hardness after quenching which in turn is determined by the carbon content [18] and the alloy/tramp element content [13]. The tramp elements have individual effects that are additive and increase with particular alloying element content [5]. This is summarized in equation (2) [17].

at the core characteristic of TMT bars. Additionally, almost all alloying /tramp elements in steel (with the exception of cobalt) tend to reduce M_s and M_f temperatures, making it easier for martensite to form deeper in the section and at lower temperatures and increasing the dislocation density in the martensite. Alloying elements also reduce the critical cooling rate with a similar effect [2]

R2 and R7 also show a wide difference in the micro-hardness between one extreme and the other (see R7 in Table 1). For presumably the same quenching conditions and equalizing temperature, the only possible reason is

variation in composition between end A and end B, leading to different critical diameters (hardenability). This is reminiscent of the recycled origin of the steel bars and their tramp element content [16]. An examination of the composition of the ends of R7 is as in Table 2. Important strengthening elements like manganese and silicon vary substantially between the two extremes leading to lower hardenability for end B than end A.

R7 is an example of the asymmetry in properties in some bars which repeats itself to an extent in R1 and R16 (Fig. 3). While this could be due to unequal quenching and/or tempering conditions, the more likely cause would be variation in composition across the diameter equally the result of unequal distribution of tramp elements across the relatively large diameter of the bars, resulting in differences in hardenability.

Finally and of great importance is that all the samples met the strength and ductility requirements as depicted by the σ_u and the (σ_u/σ_y) ratio. This actually shows that on the whole, the unequal properties kept within the standard values in accordance to EAS 412-2:2005.

5. CONCLUSIONS AND SUGGESTIONS

One of the biggest achievements in the Ugandan manufacturing sector is the growing production of TMT bars and the gradual but steady replacement of twisted bars with strong and ductile tempered and quenched properties.

Noteworthy, however is that the hardenability of the recycled steel, a most important property in the outstanding features of TMT bars, is affected by the high tramp element content. The most immediate course of action to overcome this is the improvement of the ladle refining process to include a substantial amount of gas or/and electro-magnetic refining. In the long run, however, the use of cleaner virgin ore currently beginning to be exploited is the ultimate solution. The use of direct reduced iron (DRI)/sponge iron and hot briquette iron (HBI) from the locally available iron ore will make it possible to dilute the recycled steel to the right composition, deterring the progressive accumulation of residual elements in scrap and making the steel less tramp element laden.

There is also need to improve on the sorting process prior to the melting of scrap. The quality of scrap in Uganda has gone down so much owing to the low supply and the growing demand that practically all kinds of inappropriate scrap are on the market. The employment of specialized scrap dealing and sorting would enable the quality of scrap to be classed so that upon purchase, the average composition of the scrap is known.

Additionally, the effects of the tramp elements: Arsenic, Bismuth, Cadmium, Antimony, Tellurium and Zinc can be reduced or neutralized with the addition of Cerium. The amount of Cerium necessary to counteract their harmful effects depends on the sum of all the tramp elements present although typically, about 0.01% Ce is sufficient [20]. It may be added along with traditional ferromanganese (FeSiMg).

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