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EvaluatingTMT Recycled Steel ReinforcementBar Quenching Parameters from Martensite RingVolume and Bar Strength.

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***Abstract**: Thermo-mechanically treated (TMT) bars owe their properties to the martensite and the pearlite/ferrite metallurgical strata into which their cross-section is divided. Since each stratum contributes a decisive part in the mechanical behavior of the steel bar, it is possible to use their properties to predict and control the bar performance by modifying the relevant layers.In this study, thecorrelation between the strength of TMT bars and their martensite ring volume fraction was investigated.The potential use of this relationship in the setting of relevant quench-box jet variables during the manufacture of TMT bars was shown.This was done by determining the depth of barsection annulus in samples in the 500 to 550 Mpa yield strength range using a hardness tester and then with atensile testing machine, the corresponding bar strengthestablished and an excel XY-chart plotted. The bars were also subjected to specto-analysis. The martensite ring percentage area ranged between 28 and 32%for 500 to 550 Mpadepending on bar chemical composition. The resulting exponential equation* $y = 277.67e^{0.0273x}$*returned a 0.95 coefficient of determination. The corresponding equationusable in the setting of relevant quench-box jet variables in the generating of TMT bar section profilewas developed.*

***Keywords**: Quenching, Martensite ring, Critical cooling rate, thermo-mechanical treatment, steel*

1. Introduction

Thermo-mechanically treated (TMT) bars are cylindrical multi-layer steel compositesthat derive their strength from the quenchingprocess to which they are subjected immediately after hot-working;

taking advantage of theremnant rolling heat. The quenching, whose working parameters are currently established by try and error methods, is followed by a meticulously controlled temperingregime which then generates a tough martensitic outer surface of a pre-determined depth. This layer surrounds a softer inner core consisting of chiefly ferrite and pearlite with intermediate products such as bainite sandwiched between them(Fig.1). The overall result is a steel bar whose strength can be controlled by modifying the percentage volume occupied by these phases.This is because theharder surface annulus results from the martensite volume fraction which gives rise to the elevated strength that characterizes the TMT bars while the softer, ductile inner core accounts for theirbendable and weldable nature[1].

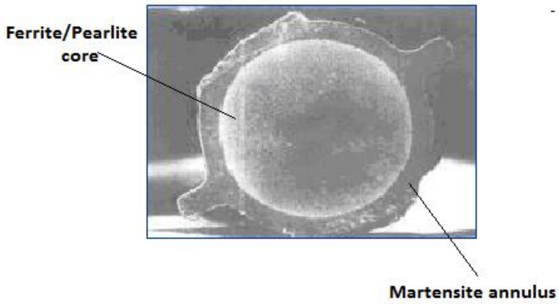

Fig.1: Cross-section of TMT bar

The thermo-mechanical treatment process comprises three stages: surface quenching, self-tempering and the final cooling (Fig.2).

The first stage isoriginatedby the finishing rolling temperaturewhich is a function of thereheating temperature sinceafter reheating, the billet rolling temperature, usually up to 1200°C, drops to the finishing rolling temperature, typically in therange 900 to 1100°C.This, during the TMT process, becomes the quenching temperature, T_q (Fig.2 & 3).

The heat removal rate at the bar surface, the quenching timeand the critical cooling rate are the other governing factors in this phase [2]. Together, thesedictatethe volume fraction of the martensiteafter quenching whichin turn,is closely tied to the steel chemical composition.

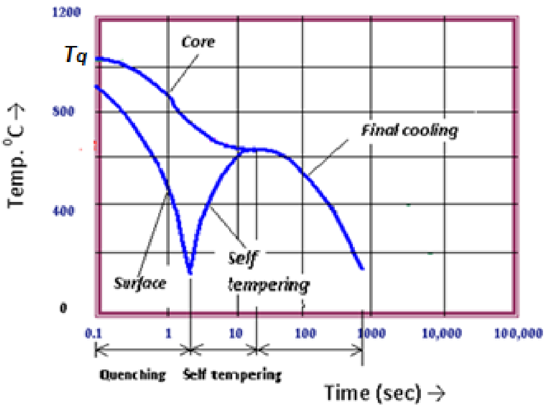

Fig.2: TMT Cooling Process (Markan, 2004)

For a given carbon content, the required quench severity (Fig.3) and the extent of the subsequent tempering aredictated by the projected steel bar strength and ductilityrespectively [3].

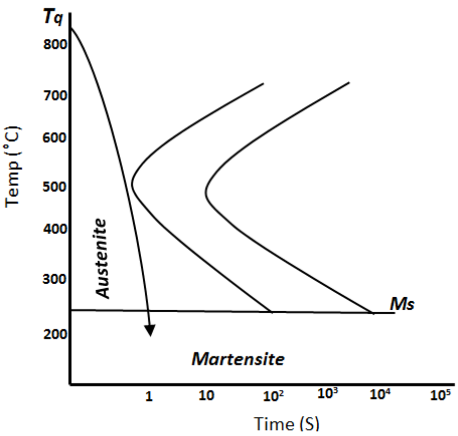

Fig.3: TTT Diag. for Low Carbon Steel

The influence exercised by the alloying element content of the steel which for recycled steel components, will depend on the level of the tramp elements and factors into the corresponding steel martensite start temperature, M_s of the TTTcurve (Fig.3), can be appreciated in equation *i*)[4].

$$\boldsymbol{Ms(°C) = (512 - 456)\%C - 16.9\%Ni + 15\%Cr - 9.5\%Mo + 217\%C^2 - 71.5\%(C * Mn) - 67.6\%(C * Cr) \ldots .(i)}$$

Importantly, these elements in combination with carbon, will determine the depth and distribution of hardness across the barcross-section [5]. The subsequent hardness after tempering, $H_t$is alsorelated to the hardness after quenching H_q. The overall combination of these factors then contributes to hardness after tempering as in equation *ii*).

$$\boldsymbol{H_t = 2.84H_q + 75(\%C) - 0.78(\%Si) + 14.24(\%Mn) + 14.77(\%Cr) + 128.22(\%Mo) - 54.0(\%V) - 0.55T_t + 435.66\ldots .ii)}$$

For reasons of economic viability, the vast majority of the reinforcement bars contain a substantial amount of recycled steel whose chemical content fluctuates ample and unpredictably owing to their inherently varying tramp element content.

The second stage directly depends on the tempering temperatureT_t, which is the maximum core temperature achieved at the end of the quenching process in stage one.This phase hinges on the steel bar conductivity (Fig.2). It results from the tendency for the bar equalize its temperature across its section; the heat from the core fostering the tempering of the martensite.

The bar is then allowed to cool to room temperature in the third stage (Fig.2). During this process the residual austenite in the bar core is transformed to pearlite and ferrite.

The fact that the tramp element content in recycled steel is highly unpredictable makes the predetermination of the martensite annulus and the related steel bar strength difficult and therefore complicates the presetting of the quench severity through the setting of the quenching water flow rate and pressure. The establishment of an imperial relationship between steel strength and the martensite ring size,used in conjunction with equation *i*), facilitates the determination of the essentialcooling values.

In this paper, a relationship is established between the martensite ring volume as a percentage of the bar section area, the reinforcement bar strength and the requisite quenching parameters.

2. Methods and equipment

Thirty *Φ*20mm TMT steel reinforcement bars selected at random were cut to 300mm lengths. Discs of10mm thicknesswere cut from each of the bars perpendicular to the bar axes and their chemical composition determined using a Spectrol Lab. Spark Spectrometer. With an HR-500 Mitutoyo hardness tester, micro-hardness wasdeterminedat 1mm intervals on the 10mm disc pieces from surface to core and plots of hardness to radial distance were made.

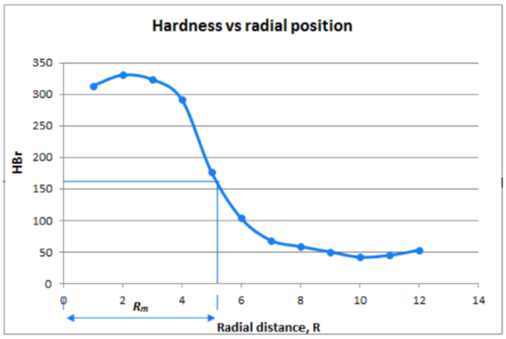

Fig.4:Micro-hardness plot

Usingthe hardness value for pearlite as 160HBr [2], the corresponding martensite ring thickness $R_m$was located at the first appearance of pearlite (Fig.4) and the martensite volume percentage calculated as $\frac{A_b - A_p}{A_b}$ where A_b and A_p arethe cross-section area of the bar andthe inner core (pearlite) zone respectively (Fig.5).

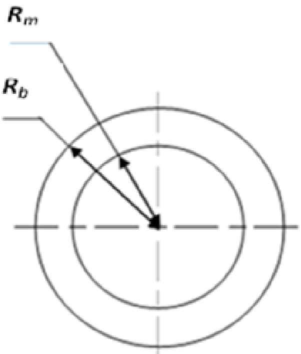

Fig.5: Radii of anallus

The 300mm pieces were subjected to tensile testing and the corresponding force-displacement curve plotted using an MFL SYSTEM hydraulic universal tensile testing machine.

Values of ultimate strength σ_u were plotted against the calculated martensite volume percentage ratios$\frac{R_b^2 - R_p^2}{R_b^2}$and the line of best fit inserted using Microsoft Office Excel XY-chart.

3. Results and discussion

Table 1: Chemical commposition of steel bars

C	Mn	P	S	Cr	Cu	Mo	Ti	B	C_{eq}
0.22	0.67	0.043	0.052	0.12	0.28	0.0193	0.001	0.0015	0.34

Table 1 shows the average chemical composition of the TMT bars used while in Fig.6 the final plot of the steel bar ultimate stress against the calculated volume fraction of martensite can be appreciated. The resulting exponential curve $y = 277.67e^{0.0273x}$obtained returned a0.9 coefficient of determination.

The martensite ring area percentage range Δm (Fig.6) corresponding to the annulus radius R_m for the 500 to 550MPa yield stress (600 to 660MPa ultimate stress) level stipulated for TMT steel reinforcement bars [6] was shown to be in the range 28.2 to 31.8% for the bars tested.

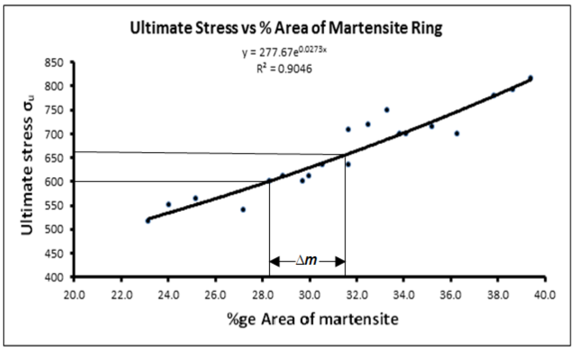

Fig.6: Ultimate stress vs martensite annalus area fraction

For a given scatter of yield (ultimate) steel bar strength, the range in which the martensite annulus thickness lies is read off the plot. With an established steel bar composition, the martensite start (*Ms*) temperature can be determined using equation *i)* and a tempering regime inserted accordingly. Using the TTT curves (Fig.3), thecritical cooling rate,$C_r$can be established that produces the depth which when subjected to the tempering regime, engenders the corresponding ring thickness Δm (Eq.*ii*).

The quenching rate indicated by the TTT diagram dictates the speed at which heat must be withdrawn from the bar surface in order to obtain a given depth of martensite in the bar section and consequently, the setting of the water flow rate $R_w$from the quenching jet orifices. $R_w$can be evaluated by equating the sum of the heat removal rate corresponding to the critical cooling rate C_r (Fig.3)with the jet cooling effectdue to the heat removedby the quenching spray and can be expressed as:

$$R_w = \pi v_b d_b \frac{\left[\left(\frac{C_r}{4} d_b \rho_s\right) s_s + h\Delta t_s\right]}{s_w \Delta t_w \rho_w} \ldots\ldots\ldots\ldots\ldots iii)$$

where:

$\rho_s$the density of steel
$\rho_w$the density of water
$V_b$speed of the bar
$d_b$diameter of the bar
h heat transfer coefficient
$s_w$specific heat of the water
C_r is the critical cooling rate
Δt is temperature gradient.
s_s the specific heat of steel

4. Conclusion

There exists a relationship between the martensite ring and the strength of TMT bars which when established for a given steel composition can be utilized to establish the quenching regime represented by the setting of the pressure levels and the subsequent flow rates of the spray nozzles in the TMT rolling mill.These rates have ranges that are used in actual practice, typically 150 to 750m^3/h at 9 to 14 bar respectively[5],which appreciably vary widely so that the technical decision to position the actual setting at a value is dictated by such important variables as Δm as well as their bar diameters. This ultimately has a bearing on the steel bar travel speed through the rolls which also has a ruling working range varying widely between 6 and 30m/s [8]whose precise value would depend on the required cooling intensity and the bar diameters.

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