Correlation between Ultimate Strength and Martensite Annulus in TMT Bars

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Abstract
Following the rolling and heat treatment processes, TMT bars have a tempered martensite outer with a ferrite pearlite core. The martensite zone is at least twice the tensile strength of the pearlite. This research was aimed at establishing the regression between the thickness of the outer layer and the overall ultimate strength of the steel bar. Thirty bars of TMT were selected and subjected to tensile testing. Polished sections of these bars were subjected to surface micro-hardness tests. A plot of hardness against the radial displacement along the section of the bar was made to enable determination of the 50% position. The thickness of the martensite zone up to the 50% position was made against the ultimate strength of the bar in each case. A direct proportionality in $y = 438.36\,X + 104.3$ resulted at 0.9278 determination to show that the martensite ring thickness is directly proportional to the ultimate strength of the thermo mechanically treated bar.

Keywords: steel; thermo mechanical treatment; martensite; ultimate strength; annulus

1. Introduction
In thermomechanically treated (TMT) bars, steel is quenched as soon as its hot forming process is completed at the final finishing stand of the mill train. Besides the steel composition, the speed and duration of the quench determine the depth of hardening, having been preset by adjusting the water flow rate with the aid of appropriate pyrometers, so as to leave a mainly pearlite and ferrite core typically profiling as in Fig.1 [1].

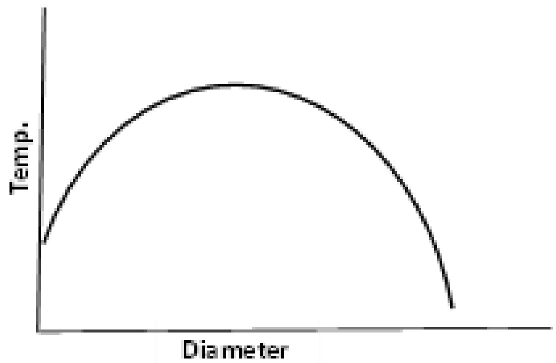

Fig 1: Temperature Distribution after Quenching

This is then followed at the cooling bed, by a period in which the heat from the core is allowed to temper the martensite formed during quenching and a third stage in which the whole bar section, having acquired a uniform temperature, is left to cool to room temperature in order to relieve it of internal stresses.

This is more applicable to those stresses due to volume changes associated with the transformations between M_s and M_f temperatures introduced during the rapid quenching stage. This combination of phenomena enhances the bar tensile and yield values and guarantees ductility and toughness in the bar, without having to resort to special alloying of the reinforcement steel bar material [2].

The final product is therefore similar to a hollow cylinder of tempered martensite with a pearlite-ferrite core. This compound structure has its overall strength dictated by the strengths of the two main components which in turn depend on the treatment modes. Martensite, when tempered, partially decomposes into ferrite and cementite so that it will not be as hard as just-quenched martensite but is much tougher and is finer-grained. Martensite is up to twice the strength of pearlite with a similarly high elastic modulus.

The result of the tempering process is a combination of pro-eutectoid ferrite and pearlite core, whose tensile strength lies in the range 950Mpa and an outer ring who's tempering yields a martensite of tensile strength range between 910 and 1075 Mpa depending on the martensite volume fraction, V_m [3]. Experiment has shown that the yield strength and elongation of the thermomechanically treated reinforcement bar increase with growing V_m, peaking around 50% martensite and reducing with further increase in V_m. [4]. For a given carbon content, V_m is a function of the quenching temperature and time as well as the ulterior tempering regime [5].

The purpose of this research is to examine and quantify the relationship between the hardened layer on the outside of the TMT bars and the overall bar ultimate strength which finally would provide an avenue to determine the strength of the bar using non-destructive methods, given the martensite volume. It must be remembered that there have been empirical relationships between hardness and tensile strength which have frequently been used to simply and cheaply determine approximate values of uniform composition bars. Equation 1) has been in common use.

$$\sigma_u = k.H \dots\dots\dots 1)$$

Where H is the hardness on the Brinell scale and k is a coefficient between 3.38 and 3.55 for steel [6]. This relationship is evidently not expected to hold here given the composite nature of the thermo mechanically treated reinforcement steel bars.

The thickness of the martensite zones can be determined from a micro-hardness plot across the bar surface since the hardness values are expected to make a sudden change at the boundaries of the two zones [7].

2. Methods and Equipment

Thermo mechanically treated bars of 12mm diameter, cut to 300mm lengths, were selected from different outlets in the country with carbon content $0.17 \leq \%C \leq 0.29$, the composition more propense to formation of a fully martensitic structure. Tensile tests were carried out on the pieces using a Blue Star UTN-(E) 100 Universal Testing Machine with a constant crosshead speed of 0.025 mm/s and the ultimate strength values recorded.

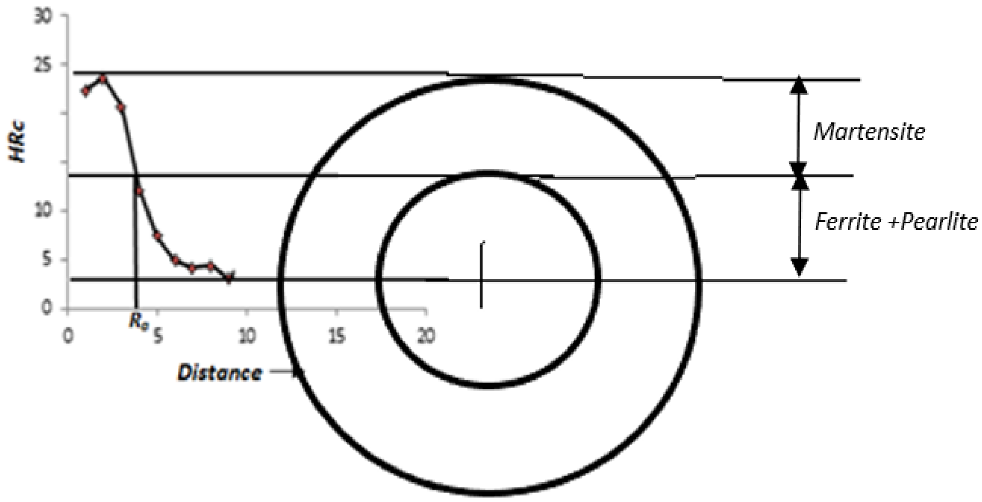

Fig 2: HRC vs Radial Distance

Parts of the same bars were cut into 6 mm thick discs and their faces hand ground parallel and fine finished with a universal surface grinder. Micro-hardness tests were carried out on their cross-sections using a 150kg load on a 120° conical indenter across their radii from surface to core with an HR-500 Mitutoyo Rockwell hardness tester. Their martensite zones were determined from the hardness-distance curves. The radial distance at which hardness dropped by 50%, also used as the Jominy length where 50% martensite occurs, was designated to be the martensite layer boundary and the thickness of the martensite layer, R_a determined from the hardness-thickness curve plot as in Fig. 2.

The resulting ultimate strength readings (Fig.3) were plotted against the martensite zone radial distance values for each bar and the line of best fit constructed.

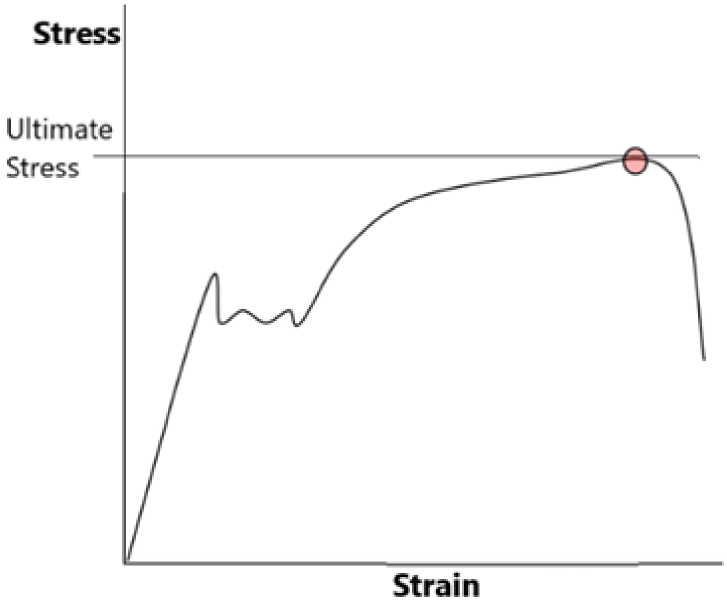

Fig 3: Ultimate Tensile Stress

The manner in which the hardened annulus varied with the strength of the bars is as shown in Fig.4. Differences in composition as well as fluctuations in the thermal mechanical processing expectedly make the martensite layers different thicknesses and hardness.

3. Results and Discussion

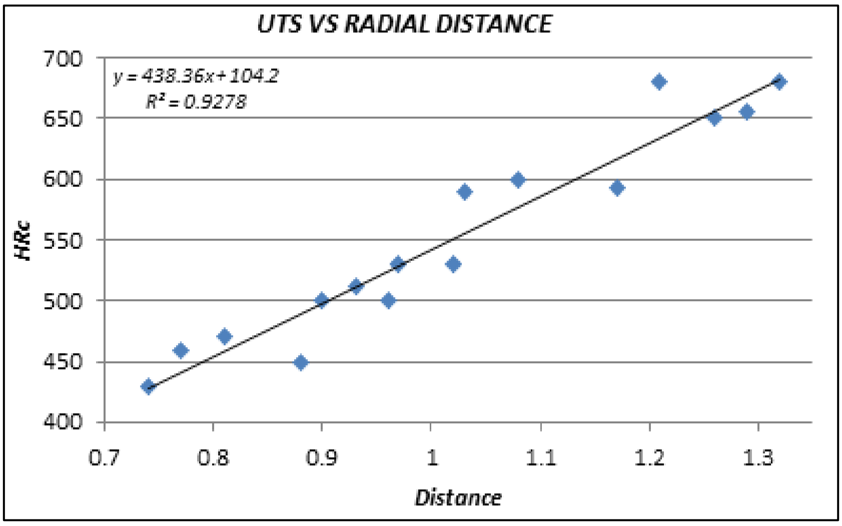

Fig 4: Ultimate Strength vs Martensite Ring Thickness

The presence of the martensite annulus makes the physical meaning of the bar cross section different from that of the ordinary bar with uniform cross-section features of similar composition. This too determines the ductility and toughness of the composite bar and consequently accentuates the role of the thermo mechanical process.

Given the ductile nature of the pearlite-ferrite dominated core, and the contrasting hard and fragile martensite external, crack propagation and growth at fracture is actually different, both in intensity and orientation for the two zones. This would grossly influence the fracture mode be it in monotonic or cyclic loading regimes [8]. Thus, even though crack initiation, propagation and growth in relatively hard and brittle martensite is easy due to its stressed, highly unstable nature, being a supersaturated solid solution of carbon in ferrite with a body-centered tetragonal (BCT) structure, the subsequent crack travel through the neighbouring pearlite/ferrite zone is restrained by the dissimilarity of the lattice and its crystal graphically greater stability. This explains the greater crack resistance of thermo mechanically treated steel in comparison to micro alloyed bars with comparable strength. It is also known that a brittle phase such as cementite becomes a fracture initiation site, and thus the fracture toughness depends on the size of brittle phase [9].

The fact that the total tensile strength of the thermo mechanically treated bar is a function of the volume fractions of the different constituent zones and their respective individual strengths already suggests that the martensite ring thickness plays some part in the ultimate bar strength in proportion to its volume fraction as in:

$$\sigma_u = \sigma_{u,m}.v_m + \sigma_{u,p}.v_p \;\ldots\ldots\ldots 2)$$

Where:

σ_u is the ultimate strength of the TMT bar,

$\sigma_{u,m}$ the ultimate strength of the martensite ring,

$\sigma_{u,p}$ the ultimate strength of the pearlite/ferrite zone.
v_m and v_p the volume fractions of the martensite and pearlite/ferrite respectively.

The volume fractions are a function of the radii of the different constituents, martensite and pearlite/ferrite [10]. It would follow that in the final analysis, there exist some intrinsic relationship between the martensite ring dimensions and the ultimate strength of the bar.

4. Conclusions

There is a direct relationship between the martensite ring size in the thermo mechanically treated bars and the ultimate strength of the composite steel bar. A linear regression has been established as $y = 438.36\,X + 104.3$. This is likely to be dependent on the range of composition, especially the carbon content since it plays a major role in the hardenability of the steel. The crack propagation properties of the two zones that constitute the composite thermo mechanically treated bar make this observation hard to deduct even form equation 2) in view of the different natures of the crystal composition of martensite and pearlite.
This plot can be used to determine the strength of the steel bar by simply determining the martensite ring if the tensile testing machine is not available or in cases that tensile testable samples cannot be obtained especially as they would be subjected to destructive testing.

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