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Topic – Study of mechanical properties of FE550SD using leaner chemistry.

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The training was a great exposure to know how things read in textbooks are implemented in the industry.

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It was a pleasure working with such an organization and I will be looking forward to be a part of it even in the future.

INTRODUCTION

TMT stands for thermos mechanically treated steel. They are made up of two cores – a hard outer core and a soft inner core. It is mostly used in construction in concrete reinforcement structures, flyovers, dams, bridges, thermal plants, industrial plants, etc. It is a combined thermal and mechanical treatment to improve attributes such as yield strength, ductility, and stiffness.

It is frequently employed in construction of structures in humid environments as well as long-lasting, high-strength, high-quality construction due to its corrosion resistant qualities. Some features of TMT are :-

- They contain a carbon ratio less than 0.5% resulting in great tensile strength and less brittleness.
- It helps in saving steel up to 17%.
- TMT bars are less expensive than other varieties of steel bars.
- They are fire resistant and hence in high demand.
- They have high fatigue strength, they may be bent into desired shape during production.
- They can be used in any type of building projects.

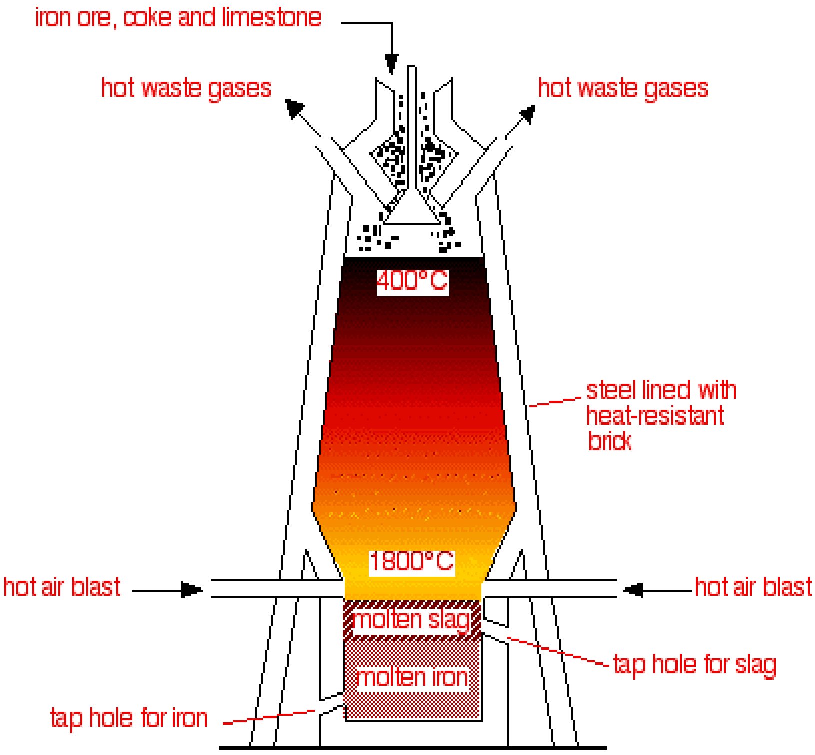
MANUFACTURING OF TMT BARS

TMT Steel stands for Thermo Mechanically Treated Steel. Hard outside and softer inner core are the two surfaces of the TMT bar. It is mostly used in concrete reinforcement structures, flyovers, dams, bridges, thermal plants, industrial structures and hydel power plants.

The manufacturing process of Thermo Mechanical Treatment includes five steps:-

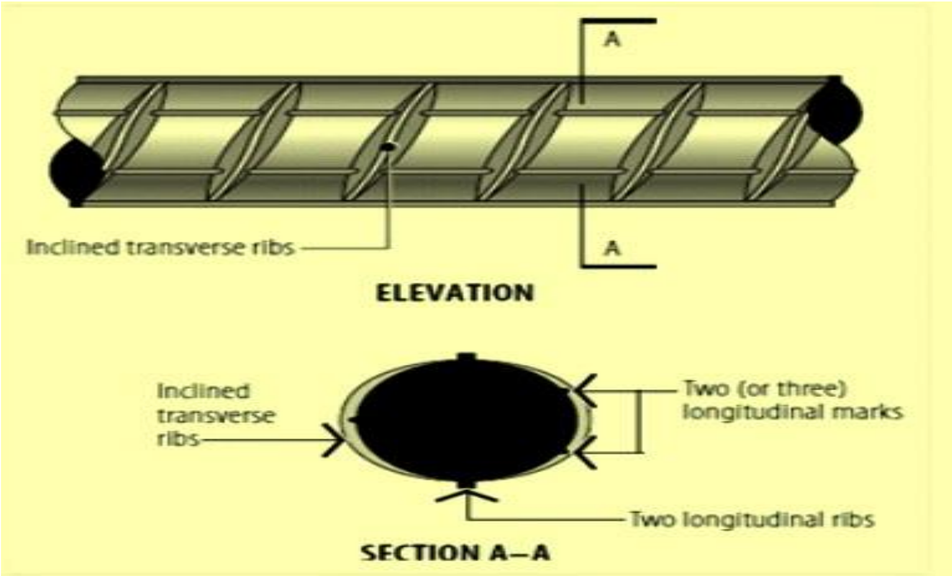
- Extraction of iron from its ore.
- Heating, rolling and forming of a reinforced bar.
- Quenching.
- Self-tempering.
- Atmospheric cooling.

Step 1- Extraction of iron from its ore:



Raw materials like iron ore, coke or flukes are utilized to extract iron that is kept in the molten state. After this, molten iron is subjected to pre-treatment and converted to steel in a converter and is then subjected to ladle heating for refining the chemistry of the steel. Then, the molten steel is poured into a casting machine to produce billets of about 130 mm2 or more.

Step 2 - Heating, Rolling and formation of reinforced bar:



The steel billets are made by heating to 1200°C [2192 F] to 1250°C [2282 F] and are rolled to reshape the billets into the final size and shape of the reinforced bar before passing the billets through a rolling mill stand.

Step 3 - Quenching:

The hot reinforced bar leaving the final rolling mill stand is instantaneously quenched. Quenching process stops the occurrence of undesired processes such as phase transformations. It completes this by minimizing the time frame during which these undesired reactions have a higher chance of occurring. A sudden drastic change in temperature toughens the outer layer of the steel bar improving its tensile strength and durability. It is because, quenching converts the outer surface of the reinforced bar to Martensite, a hard form of steel and causes it to shrink that in turn pressurizes the core and helps to form the correct crystal structures. Therefore, the surface of the quenched bar becomes cold and hardened whereas the core still remains hot.

Step 4 - Self- tempering:

A temperature gradient is formed across the cross-section of the quenched bar after leaving the quenching box. As an outcome heat flows from the core at a relatively higher temperature to the outer surface. This causes the correct tempering of the outer martensitic layer into a structure known Tempered Martensite and the formation of an intermediate ring of Martensite and Bainite. The core still stays in the austenitic state at this stage.

Step 5 - Atmospheric Cooling:

The bars are subjected to atmospheric cooling to equalize the temperature difference between the soft inner core and the hardened exterior after the self-tempering process. When the bars are completely cooled down, the austenitic core gets transformed into a ductile ferrite- pearlite structure.

GRADES OF TMT BARS

There are various grades of TMT bars manufactured by various steel companies in the market. TMT bars have different grade based on their yield strength and rigidity. Grade of TMT bar is represented as Fe415, Fe500, Fe550, Fe600, Fe550D, Fe550SD, etc. This grade represents the strength and rigidity of the bar, specifically the yield strength of reinforcement.

It is very necessary to choose the right grade, depending upon the type of structure.

TMT bar grade Fe415 :-

In TMT bar grade Fe 415, Fe denotes made of iron, numerical figure 415 stand for their minimum yield strength in N/mm2. This grade of TMT bar commonly used for construction of houses and residential building, they have uniform elongation which make them earthquake resistance. hence they are perfect to build home in earthquake prone area.

Mechanical properties of TMT bar grade Fe 415:-

1) their yield strength (fy) is 415N/mm2

2) ultimate tensile strength (fu) is 485N/mm2

3) elongation is 14.5

4) YS ratio is 1.16.

Chemical composition of TMT bar grade Fe 415:- it is made of iron mixed with some amount of carbon, sulphur, phosphorus materials by mass, carbon contain is about 0.3%, Sulphur contain is about 0.06%, Phosphorus contain is about 0.06% and S+P is about 0.11%.

TMT bar grade Fe500:-

In TMT bar grade Fe 500, Fe denotes made of iron, numerical figure 500 stand for their minimum yield strength in N/mm2. This grade of TMT bar best suitable for construction of multiple storey and commercial building and it is resistant to corrosion.

Mechanical properties of TMT bar grade Fe 500:-

1) their yield strength (fy) is 500N/mm2

2) ultimate tensile strength (fu) is 545N/mm2

3) elongation is 12

4) YS ratio is 1.09.

Chemical composition of TMT bar grade Fe 500:- it is made of iron mixed with some amount of carbon, sulphur, phosphorus materials by mass, carbon contain is about 0.3%, Sulphur contain is about 0.055%, Phosphorus contain is about 0.055% and S+P is about 0.105%.

TMT bar grade Fe550:-

TMT bar grade Fe 550:- in TMT bar grade Fe 550, Fe denotes made of iron, numerical figure 550 stand for their minimum yield strength in N/mm2. This grade of TMT bar best suitable for large-scale project like bridge and construction of heavy underground structure.

Mechanical properties of TMT bar grade Fe 550:-

1) their yield strength (fy) is 550N/mm2

2) ultimate tensile strength (fu) is 585N/mm2

3) elongation is 10

4) YS ratio is 1.06.

Chemical composition of TMT bar grade Fe 550:- it is made of iron mixed with some amount of carbon, sulphur, phosphorus materials by mass, carbon contain is about 0.3%, Sulphur contain is about 0.06%, Phosphorus contain is about 0.06% and S+P is about 0.11%.

TMT bar grade Fe600:-

In TMT bar grade Fe 600, Fe denotes made of iron, numerical figure 600 stand for their minimum yield strength in N/mm2. This grade of TMT bar best suitable for large scale industrial construction projects. This is the highest strength TMT bar available in market.

Mechanical properties of TMT bar grade Fe 600:-

1) their yield strength (fy) is 600N/mm2

2) ultimate tensile strength (fu) is 660N/mm2

3) elongation is 10

4) YS ratio is 1.10.

Chemical composition of TMT bar grade Fe 600:- it is made of iron mixed with some amount of carbon, sulphur, phosphorus materials by mass, carbon contain is about 0.25%, Sulphur contain is about 0.04%, Phosphorus contain is about 0.04% and S+P is about 0.75%.

TMT bar grade Fe 550D:-

In TMT bar grade Fe 550D, Fe denotes made of iron, numerical figure 550 stand for their minimum yield strength in N/mm2 and D stand for higher bar ductility. This grade of TMT bar best suitable for large scale industrial construction projects. It is best suitable for use in earthquake prone area.

Mechanical properties of TMT bar grade Fe550D:-

1) their yield strength (fy) is 550N/mm2

2) ultimate tensile strength (fu) is 585N/mm2

3) elongation is 16.

TMT bar grade Fe500SD:-

In TMT bar grade Fe 500SD, Fe denotes made of iron, numerical figure 500 stand for their minimum yield strength in N/mm2, D stand for higher bar ductility and S stand for super ductility. This grade of TMT bar best suitable for large scale industrial construction projects. It is best suitable for use in earthquake prone area.

Mechanical properties of TMT bar grade Fe500SD:-

1) their yield strength (fy) is 500N/mm2

2) ultimate tensile strength (fu) is 545N/mm2

3) elongation is 18.

Uses of 500SD and 550D TMT bar:- D denotes ductility and SD denotes super ductility, which means these bars are highly seismically resistant with high strength. Hence they preferred to use in earthquake zone 3, 4 and 5. They have elongation above 16%, most suitable for Bridge, Dams, high rise Apartment, industrial structural, flyover, windmills, earthquake prone zone, Mountain Bridge, Railway Bridge, structure such as airport, hospitals, tunnels and concrete Road.

TEMPCORE PROCESS FOR PRODUCTION OF TMT REINFORCEMENT BARS

Tempcore process for the production of reinforcement bar (rebar) is a patented process in which the hot rolled bar is intensively surface quenched by water, immediately as the bar emerges from the last hot rolling stand of the rolling mill and during the subsequent air cooling the quenched outer layer is tempered by the dissipation of retained heat from the core.

The Tempcore process for the production of rebars has three stages. These stages of the Tempcore process are:-

(i) Quenching of the surface layer
(ii) Self-tempering of the martensite
(iii) Transformation of the core.

The processes are explained briefly below:-

First stage(Quenching of surface layer) :-

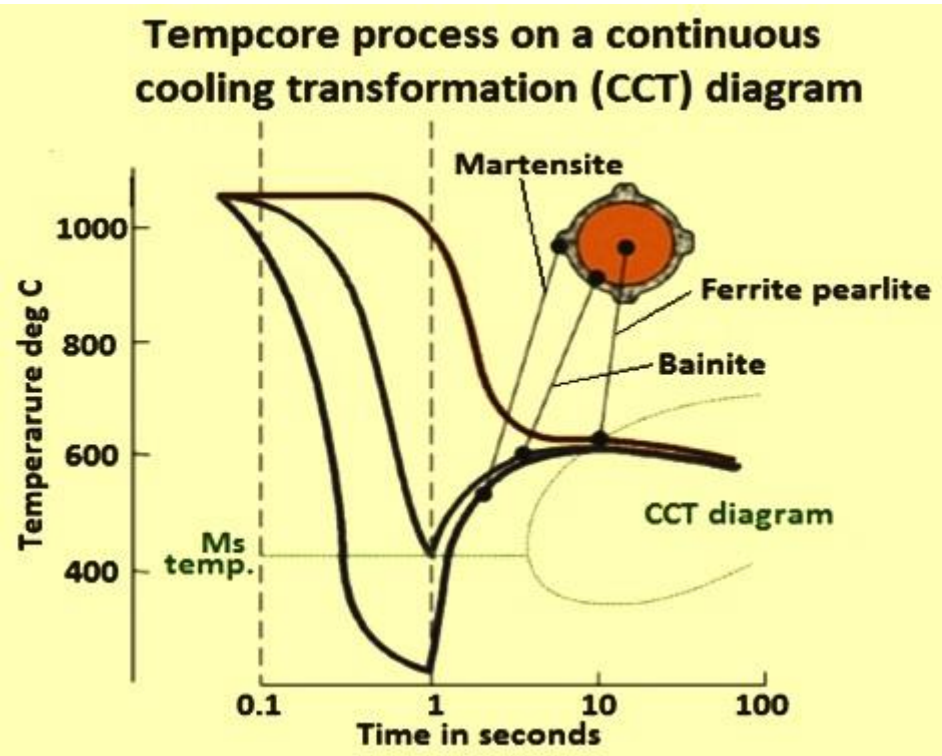
The rebar leaving the last stand of the hot rolling mill passes through a special water cooling section. The cooling efficiency of this installation is such that the surface layer of the rebar is quenched into martensite while the core remaining austenitic. The quenching treatment is stopped when a determined thickness of martensite has been formed under the skin (outer part of the rebar section dropping below the martensite transformation starting temperature Ms).

Second stage(Self tempering of martensite) :-

The rebar leaves the intense cooling section and a temperature gradient is established in its cross section which causes heat to release from the centre to the surface. This increasing of the surface layer temperature results in the self-tempering of the martensite. The name Tempcore has been chosen to illustrate the fact that the martensitic layer is Tempered by the heat left in the CORE at the end of the quenching stage.

Third stage(Transformation of core) :-

During the slow cooling of the rebar on the cooling bed, the austenitic core transforms into ferrite and pearlite or into bainite, ferrite and pearlite. Hence, a Tempcore steel rebar is essentially a composite material consisting of concentrically disposed hard outer layer and soft core with an intermediate layer which is intermediately hardened. With relatively low carbon content, Tempcore steel rebars provides high strength, excellent ductility and weldability amongst other advantages.



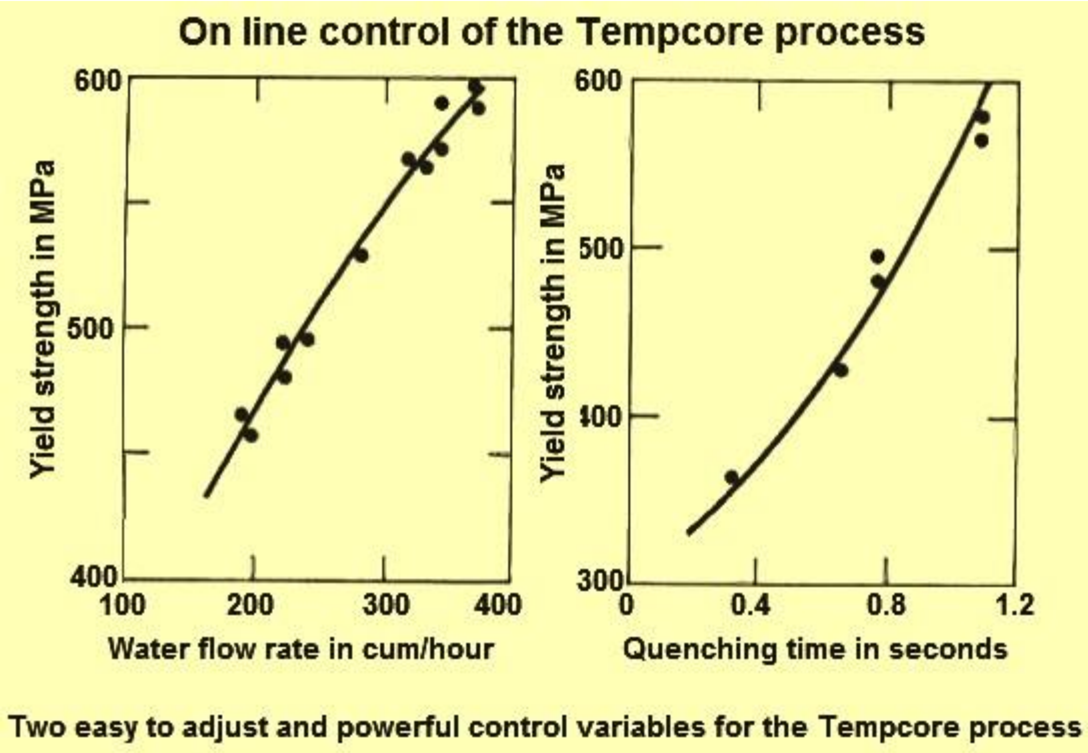
CCT Diagram for quenching

CONTROL OF TEMPCORE PROCESS

The control procedure is based on the yield strength/tempering temperature relationships, which are obtained from the results of the commissioning trials. If there is a variation of the thickness of martensite layer versus the yield strength, then the cooling power of the quenching lines has to be adjusted in order to obtain the value required for the yield strength (YS from grade + safety margin).

The pyrometers are the heart of the control of the process. The location of the tempering pyrometer is of prime importance to get measurements as close as possible to the maximum recovery temperature (maximum reached by the surface). The pyrometer located at the entry of the Tempcore box is also important to measure the variation of finishing temperature along the billet or between successive billets. A variation of 50 deg C of the finishing temperature corresponds to a variation of around 8 % of the cooling length at equal specific water flow rate, and thus to variation of the tensile properties after treatment.

The two easy to adjust and powerful control variables in the Tempcore process are water flow rate and the quenching time (Fig 6). The control of the cooling power of a Tempcore line is performed in two steps. In the first step (main control), the length of the quenching line (i.e. the number of nozzles in use) is adjusted. In order to perform an efficient control and to maintain a good homogeneity of the cooling, the nozzles to be switched off are the upstream ones. In the second step (fine tuning), the water flow rate is adjusted by acting on the main modulating valve.



On-line control of the Tempcore process

The cooling length and quenching time are linked by the rolling speed at the finishing stand. This speed is required to be maintained constant along the billet during its crossing of the quenching equipment, and more particularly when the tail of the billet is leaving the finishing stand. That is assumed by the pinch-roll located between the exit of the Tempcore box and the dividing shear. Without using this pinch-roll, when the tail leaves the finishing stand, small rebar diameters are decelerated by the water while the largest diameters are accelerated.

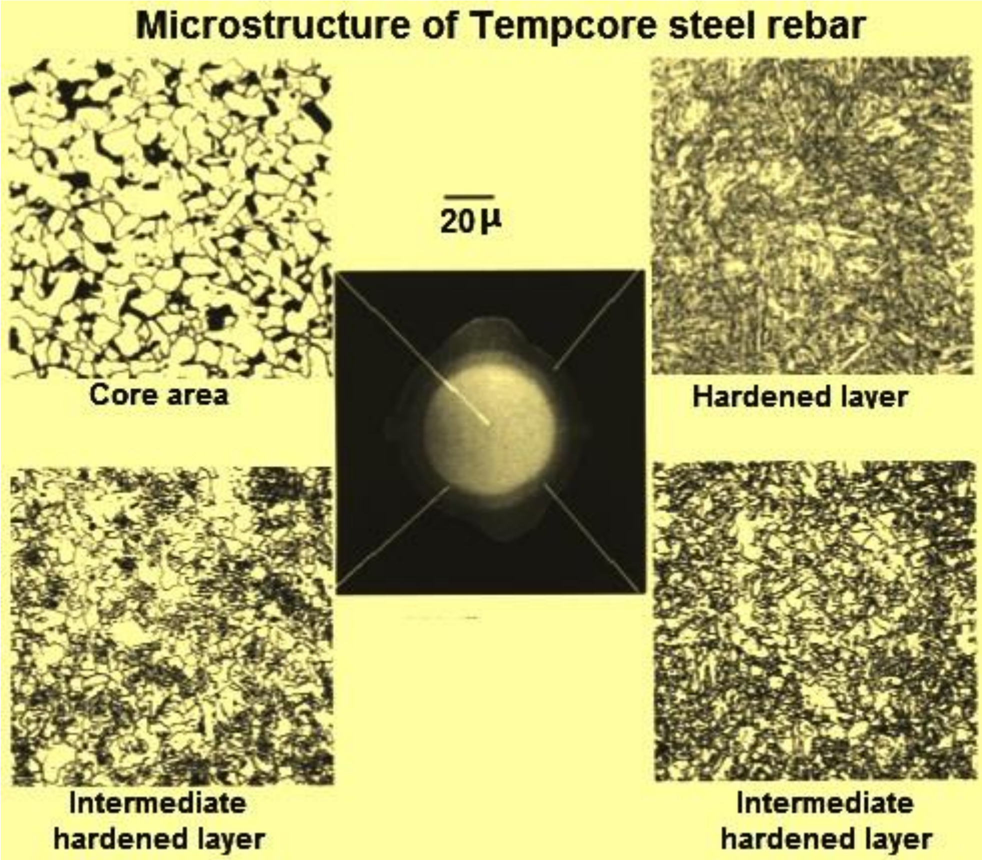
For a given diameter, the input parameters (cooling length, water flow rate, finishing temperature, and chemical composition of the steel) have influence on the output parameter of the process (tempering temperature, yield strength, tensile strength, and TS/YS ratio).

CHARACTERISTIC PROPERTIES OF TEMPERED STEEL REBAR

Various characteristics properties of the Tempcore steel rebar are described below.

1. **Type of steel** – Steels for the Tempcore rebars are basically plain low carbon steels specified for yield strength, ductility, carbon or carbon equivalent and yield to tensile ratio. The maximum and minimum specified carbon content intends to ensure weldability and hardenability. With too low carbon content, hardenability of the steel is generally not sufficient and hence more severe quenching is needed which affects the rolling mill design, e.g., speed of rolling mill, as well as the length and efficiency of cooling chamber. Carbon steel with carbon content in the range of 0.13 % to 0.24 % and the carbon equivalent (CE) of less than 0.45 % has been proved to be the best balance to satisfy the above considerations.

2. **Metallurgical phases and microstructure** – Tempered martensite in the form of packets of thin plates with martensitic morphology characterizes the hardened layer. A mixture of bainite and polygonal ferrite is in the intermediate hardened layer and polygonal ferrite and pearlite develops in the core. The microstructure is usually fine due to a relative fast cooling in the core and because of the thermo-mechanical treatment involved in Tempcore process, e.g., polygonal ferrite grains in the core region can be as small as 8 micrometers in diameter and even 3 micrometers in diameter when lower tempering temperature is used. However, coarse conglomerate of pseudo-eutectoid and Widmanstatten ferrite in the core are also possible outcome of the process. The microstructure of the Tempcore steel rebar is shown.



3. **Effects of process parameters and steel composition** – The process parameters and steel compositions play part in the final properties. Normally if the martensite layer is thicker the retained heat is less and thus the tempering is more modest so that the rebar shows higher yield strength and lower elongation. Longer quenching time, lower finishing temperature and higher intensity of quenching result in thicker martensitic layer and lower tempering temperature. Higher carbon and manganese content increases the hardenability of the steel, and hence more martensite is formed. Additionally, the strength of the tempered martensite increases as the carbon content increases.

4. **Tensile properties** – The Tempcore process can increase the yield stress for a given composition by 150 MPa to 200 MPa without losing much elongation. The tensile properties of the

bars depend on the process parameters and steel composition. The range of typical yield strength of Tempcore steel rebar is between 415 MPa to 550 MPa and elongation on a 5d gauge length is 30 % down to 25 % in the same order. The features of typical stress strain curve shows (i) elastic modulus is 200,000 MPa, (ii) the bar has marked yield point and a Luders type of yield and hence the 0.01 % proof stress coincides with 0.2 % proof stress, (iii) the ratio of yield stress to tensile strength is around 0.85, and (iv) the bar has large elongation (25 % to 30 %), large Luders strain and large uniform strain.

Tempcore steel rebar has two major features when the tensile properties are compared with those of conventional steel bar. These features are (i) higher ratio of yield strength to tensile strength, 0.85 versus 0.65 in case of conventional bar, and (ii) larger elongation, 25 % versus 4.5 % to 22 % in case of conventional steel bar.

5. **Formability** – Other remarkable properties of Tempcore steel rebar is that it has excellent bending and rebending properties. Despite the hardened outside layer, minimum bend diameter for a 180 degrees single bend is specified as 1d for 12 mm to 28 mm diameter bars and 2d for 32 mm and 36 mm diameter bars.

   Some of the Tempcore rebars (20 mm and 28 mm diameter) can even be bent without mandrel. The bars can also withstand all the bending and rebending tests after aging, satisfying the standard requirements. Further, bending operation requires less energy when compared with other types of rebars due to the low tensile strength to yield strength ratio. It is estimated that 10 % to 20 % energy is saved in bending.

6. **Weldability** – Weldability of steel is very sensitive to the chemical composition, especially to the carbon content and carbon equivalent (CE). Two popular formulas are used, one is

followed by the International Institute for Welding (IIW) and the other is given by Ito and Besseyo, covering the high and low ranges of carbon respectively.

IIW formula is $CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$ for carbon higher than 0.18 %, while the formula of Ito and Besseyo is $CE = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$ for carbon less than 0.18 %. The IIW carbon equivalent formula shows less tolerance to substitutional alloying elements than the Ito-Besseyo equation. For the weldability of steel re bars, normally the IIW formula or simplified IIW formula ($CE = C + Mn/6$) is used because of the carbon content.

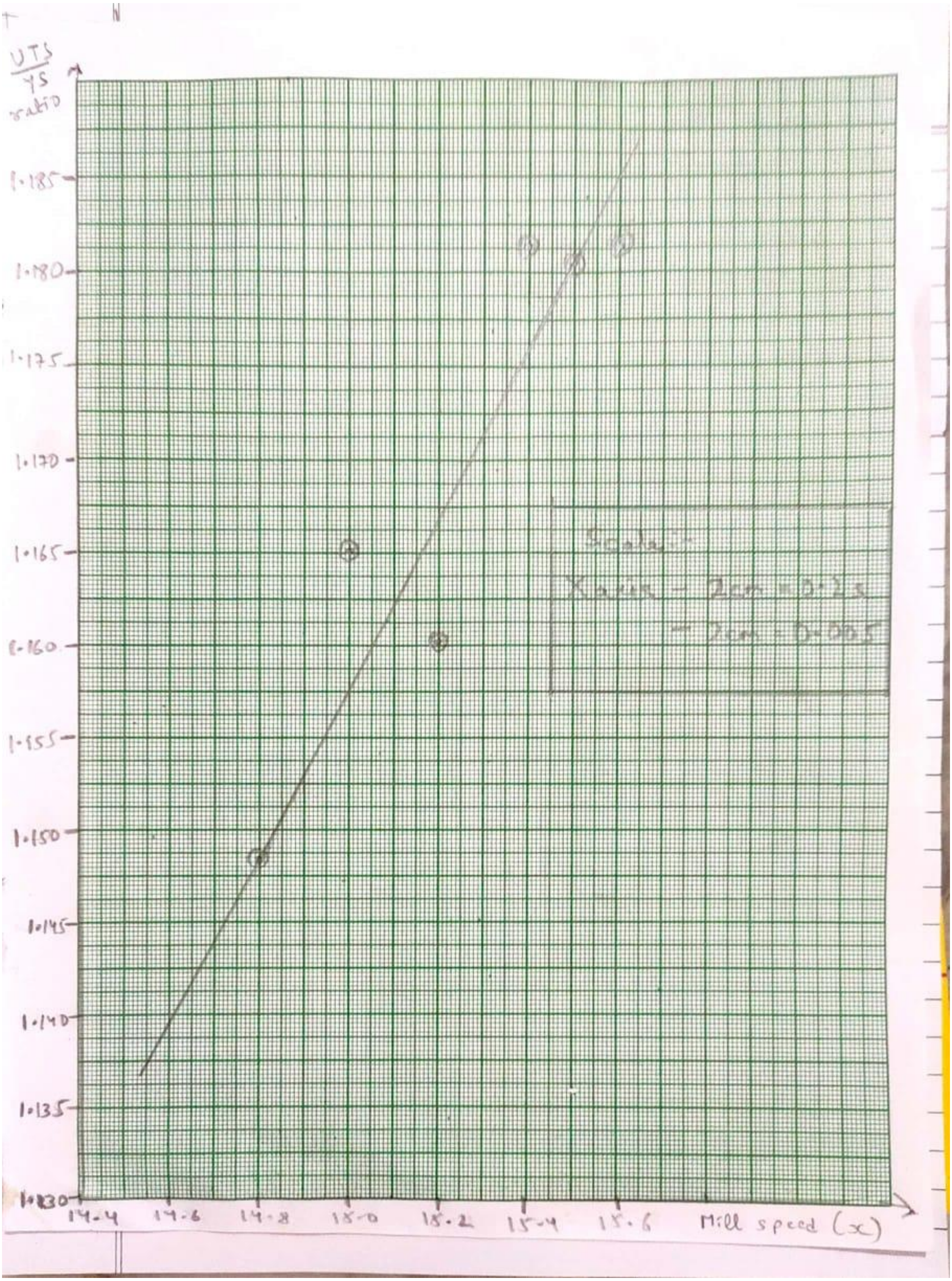
With the IIW formula, when CE is less than 0.45 % the steel is considered weldable with modern techniques. The CE of the Tempcore steel rebars is well below the critical value of 0.45 % and thus again is superior to other types of rebars.

GRAPH OF UTS/YS RATIO VS MILL SPEED

Here we will try to establish a relationship between Ultimate tensile strength/Yield stress ratio and quenching rate. The quenching rate can be altered by two ways – Increasing the rate of flow of water or decreasing the mill speed. Since the water supply is constrained we have only one method that is decreasing the mill speed. The mill speed directly affects the quenching rate which in turn affects the UTS/YS ratio.

GRADE	AVERAGE YIELD STRENGTH	AVERAGE ULTIMATE TENSILE STRENGTH	AVERAGE UTS/YS	AVERAGE MILL SPEED
Fe550D	636	723	1.148	14.8s
Fe550D	614	715	1.165	15.0s
Fe550D	620	723	1.160	15.2s
Fe550D	603	710	1.178	15.4s
Fe550D	606	713	1.176	15.5s
Fe550D	589	689	1.179	15.6s

Conclusion – So as we see from the graph that as the mill speed(quenching time) is increased the UTS/YS ratio goes on increasing. As the quenching time is increased the martensite formation increases and the strength of the TMT increases.


UTS / YS ratio
1.185
1.180
1.175
1.170
1.165
1.160
1.155
1.150
1.145
1.140
1.135
1.130
14.4
14.6
14.8
15.0
15.2
15.4
15.6
Mill speed (x)
Scale:-
X axis - 2cm = 0.2s
- 2cm = 0.005