VARIATION IN YIELD STRENGTH AND ELONGATION OF RE-BARS MANUFACTURED USING LOCAL INGOTS

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or a Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Recycling of scrap steel to produce ribbed steel bars is a common practice followed in many countries. Selection of the best composition of ingredients for the melt is a huge challenge faced by the manufacturers in the scrap recycling industry. A major problem faced by them during the recycling process is the difficulty they have in controlling the levels of undesirable residual elements such as Cu, Ni, Sn, As, Cr, Mo, Pb, etc., that come with scraps. In SLS 375:2009 and BS 4449 Standards, the 'maximum percentage by mass' of residual elements is represented by the "Carbon Equivalent Value". Carbon Equivalent (CE) value is used to understand how different alloys and residual elements affect the strength of steel. In ingot casting, a good control of ladle treatment is required for the proper control of de-oxidation and de-sulphurisation chemicals and residuals. An extensive study was carried out by referring to the literature and benchmarking the best practices of several steel makers to improve the ingot casting process. In this dissertation, the results of the experimental investigation on the effects of alloying and residual elements on yield strength and elongation of TMT bars is presented.

The experimental study was focused on identifying the most suitable mixed proportion of ferro-silicon to ferro-silico-manganese, and the best controllable range of CE values to be used during melting to ensure that the products manufactured are consistent in quality. The quantities of the main alloying chemicals mixed together are changed to make the diluted percentage of manganese content in the bath solution to be 0.8% by mass. The ingots and TMT bar samples prepared were tested to see how the Carbon Equivalent value and the mixed proportion of alloying chemicals affect the yield strength and elongation of the finished bars. It was revealed that a consistent yield strength and elongation of each TMT bar of a set can be achieved by having the Carbon Equivalent value in the range 0.37<CE< 0.4 % by mass and by mixing of ferro-silicon and ferro-silico-manganese (Si : Mn) approximately in the proportion of 1 : 4.

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LIST OF ABBREVIATIONS

Abbreviation	Description
BCC	Body Centered Cubic
BS	British Standard
CE	Carbon Equivalent
CTD	Cold Twisted Deformed
DOE	Design of Experiments
DRI	Direct Reduced Iron
EL	Elongation
FCC	Face Centered Cubic
IIW	International Institute of Welding
ppm	Parts per million
QST	Quenched & Self Tempered
QTB	Quenched & Tempered Bar
Rebar	Reinforcement Bar
SLS	Sri Lanka Standard
SLSI	Sri Lanka Standards Institution
STD	Standard Deviation
TT	Temperature Time
TMT	Thermo Mechanically Treated
UTM	Universal Testing Machine
YS	Yield Strength

CHAPTER 01

INTRODUCTION

Scrap recycling is an area that draws intense scientific attraction because of its ability to conserve earth's resources and energy and offer solutions to overcome environmental issues. Scrap recycling in the secondary steel making process plays a vital role in the production of ribbed steel bars. The main feed materials used in the secondary steel making process are scrap steel and direct reduced iron (DRI) or sponge iron. Secondary steel making is usually performed in ladles. The steel making process also includes alloy addition, de-oxidation, vacuum degassing, correction of inclusion chemistry, and homogenization. By controlling the ladle metallurgy effectively, high quality steel could be produced.

Selecting the best composition of ingredients in the melt is one of the huge challenges faced by the scrap recycling industry. For enhanced quality in steel bars, correct metallurgy of the melt is required. Carbon Equivalent (CE) is increasingly drawing the attention of the steel making industry since it can have an effect on the properties like strength and weldability in steel bars. [4]

There are presently several ribbed steel bar manufacturers who do scrap recycling. Owing to various constraints, it has however become difficult for them to achieve consistent tensile properties especially properties like yield strength and elongation in the ribbed steel bars they manufacture. The product test report issued by the Materials Testing Laboratory of SLSI presented in Table 1.1 confirms this.

Table 1.1: Test report of ribbed steel bars of size 12 mm

Parameter	Steel grade RB 500					SLS 375: 2009 Standard Specification (*size 12 mm*)
	Specimen number					
	01	02	03	04	05	
Mass per metre (kg/m)	0.875	0.871	0.871	0.854	0.870	0.848 - 0.928
Yield Strength (R_e) N/mm^2						650 > YS > 500
Individual	567.0	513.1	559.4	515.1	557.5	
Mean value $\bar{x}$	542.4					
Standard deviation [s]	26.1					
$\bar{x}$ - ks (k=1.53)	502					
Total elongation at maximum force (A_{gt}) %						(> 2.5)
Individual	4.33	8.92	6.43	7.00	4.73	
Mean value $\bar{x}$	6.28					
Standard deviation [s]	1.85					
$\bar{x}$ - ks (k=1.53)	3.4					
Stress Ratio (R_m/R_e)	1.19	1.26	1.19	1.18	1.20	(> 1.05)

Source: Report No. MT/2858/2013
Materials Testing Laboratory of SLSI

1.1 Problems and weaknesses of the existing manufacturing system in brief

1. Difficulty in deciding the most appropriate composition or ingredients in the melt with the available scraps.

2. Use of sponge iron to control the carbon content in the melt is very less due to high cost factor.

3. Use of inappropriate content of stabilizers or alloying chemicals into the charge mix.

4. Ingot manufacturing process is not standardized for consistent quality. Thereby lot of imperfections can be seen on casted ingots.

5. Difficulties arise in getting uniform yield strength and elongation through the water quenching process. Improper control of the pressure and turbulent flow of water will vary the properties of ultimate strength.

A discussion was held with the senior management and a group of metallurgists in the steel plant, to acquire a better understanding of the manufacturing process of ribbed steel bars. Through an effective brainstorming session, it was able to explore all possible causes for having inconsistent quality products, prior to planning the research component (Appendix 01).

1.2 Aim and objectives

The aim of this research was to determine the optimum range of Carbon Equivalent value and the best mixed proportion of alloying chemicals that can lower the variation in yield strength and elongation of TMT bars in a set.

Two main objectives of the research study are as follows:

1. To determine the best mixed proportion of the alloying chemicals [Ferro-Silicon (Si) and Ferro-Silico-Manganese (Mn)] for low variation in yield strength and elongation of TMT bars.

2. To determine the best controllable level of Carbon Equivalent value for reducing the variation in yield strength and elongation, while preserving the property of weldability in TMT bars.

1.3 The outline of the thesis

In order to achieve the objectives, the research was sub-divided into two main tasks.

- Improving the key parameters of the water quenching process.
- Determining the most appropriate quantities of the alloying chemicals and residuals in the charge mix

The scope of research was limited to the rebar of size 10 mm. An extensive study was carried out by referring to the literature and benchmarking the best practices of several steel makers to improve the ingot casting and quenching operations at the steel plant.

The experimental study was focused on identifying the most suitable mixed proportion of the main alloying chemicals (ferro-silicon to ferro-silico-manganese), and the best controllable range of CE values to be used during melting to ensure that the products manufactured are consistent in quality. The mixed quantities of ferro-silicon and ferro-silico-manganese were changed to make the diluted percentage of manganese content in the bath solution to be 0.8% by mass.

Improving the parameters of the water quenching process was completed as a part of the research component, prior to focusing the metallurgical aspects on variation issue.

The results of the experimental investigation on the effects of alloying and residual elements on yield strength and elongation of TMT bars was presented and the conclusions and recommendation were made at the end of this dissertation.

The significance of this research is to provide information to those who are willing to study on practical aspects of reducing the variation in yield strength and elongation of TMT bars, and to use as a guidance to improve the quality of rebar produced from available scrap.

CHAPTER 02

LITERATURE SURVEY

2.1 Introduction

Parameter control of the quenching process is one of the important tasks for achieving uniform results in yield strength and elongation of a TMT bar sample. Taguchi, in his robust design of experiment method[2] has explained some techniques which would be useful for improving and controlling the quenching parameters.

As far as the steel metallurgy is concerned, there are some factors affecting the variation in YS and elongation of TMT bars. Alloying chemicals/ stabilizers, residual elements, type of scraps steel, casting defects/ imperfections, etc., are some of these factors. There are considerable number of studies that have been carried out on those areas, and some important topics which are most related to the research study are described in this chapter.

Only a few studies have been carried out on providing partial solutions for the issue of high variation in tensile properties of the reinforcement bars. However, they do not propose any solution with respect to the mixing quantities of the main alloying chemicals in order to sustain the production of TMT bars with consistent quality.

2.2 Scrap steels

Scraps must be carefully selected for steel making. The most damaging contaminants in scrap steel are Copper and Tin. Both of these metals contribute to a weakness known as 'hot-shortness' (Hot-short steel tend to split during hot rolling).

Sulfur and Phosphorus are considered as deleterious substances (major impurities) to the mechanical properties of reinforcement steel bars; therefore, restrictions are in place in most industry standards for the maximum allowable limits of those two elements.

Phosphorus (P)

Phosphorus decreases the toughness, Impact resistance, cold formability and weldability of steels. Therefore, the maximum content is limited to 0.05% by mass.

Sulfur (S)

Sulfur causes for hot brittleness: that is, the excess amount of Sulfur reduces the ability for hot deformation (900 ^{0}C) of steel, forming the brittle FeS phase at the grain boundaries. The solubility of S is higher than the C; therefore it restricts the formation of the pearlite in the zones with higher S contents, leading a banded structure of pearlite and ferrite. Therefore, Sulfur content is also limited to 0.05% maximum.[1]

Figure 2.1 presents some pictures of the light and heavy metal scraps used for melting.

Light metal scraps

Heavy metal scraps

Light scraps in bale form

Figure 2.1: Scrap steels in various forms

2.2.1 Classification of scrap steels

Generally, iron and scrap steels use for recycling is selected based on following aspects. Any deviation from the general classification of scrap steels may be consummated by mutual agreement between the buyer and the seller. [6]

1. Cleanness:

   All grades shall be free of dirt, non-ferrous metals (foreign materials), and excessive rust and corrosion.

2. Off grade materials:

   The inclusion of a negligible amount of off grade metallic materials (which fails to a minor extent to meet the applicable requirement as to quality)

3. Residual Alloys:

   Steel scraps shall be considered free of alloys when the residual alloying elements do not exceed the following limits:

   Ni- 0.45%, Cr- 0.20%, Mo- 0.10%, and Mn- 1.65%

   The combined residuals other than manganese shall not exceed a total of 0.60 percent.

2.3 Residual elements

Residual elements like Cu, Ni, Sn, As, Cr, Mo, Pb etc., in steel cannot be removed using simple metallurgical processes as they have not been added intentionally. A major problem faced in improving the quality of steel is in controlling the level of residual elements in it. Residual elements influence processing from the beginning of casting to final heat treatment. Surface defects, interface segregation, grain boundary embrittlement and changes in hot strip properties are some of the deleterious effects caused by the presence of residuals in steel. [1]

Carbon Equivalent value is used to understand how different alloys and residual elements affect the strength and weldability of steel. The influences over the properties of steel due to the presence of residual elements identified in the CE value are described in Table 2.1. [1]

Table 2.1: The influences over the properties of steel due to the presence of residual elements identified in the CE [1]

Chromium (Cr)	Chromium is a strong carbide former and causes to obstruct the dislocation movement at elevated temperatures. Cr decreases the oxide formation tendency by forming a very coherent oxide layer on the surface, preventing further oxidation. An excess amount of Cr content increases strength, hardenability, corrosion resistance and high temperature strength of steel products. Cr in low carbon steels contributes to an increase of hot deformation resistance and delay the static re-crystallization process. Cr have adverse effect on drawability, hence higher rolling loads may be required.
Molybdenum (Mo)	Molybdenum can induce secondary hardening during the tempering of quenched steel products and hence enhances the hardenability and creep strength at elevated temperatures (Since the melting point of Molybdenum-carbide is very high, it gives high temperature strength to the product). Therefore, Mo decreases the risk for Temperature embrittlement. Mo in low carbon steel contributes to an increase of hot deformation resistance, and delay the static re-crystallization in the mill. Mo has adverse effect on drawability and hence it will create problems to the mill set-up at the end.
Vanadium (V)	Vanadium is strong carbide former. It increases the high temperature strength and hardenability (wear resistance) of steels. V has an adverse effect on drawability.
Copper (Cu)	High Cu content increases the strength and corrosion resistance. Cu is the key element for surface defects due to hot shortness. Hot-short steel tends to split during hot rolling. Therefore Cu is restricted to a Maximum level of 0.80% by mass.
Nickel (Ni)	Ni increases the strength, toughness (even at sub zero temperatures) and hardenability. Ni compensates the Cu effect if present in about the same content. Ni is an austenite former.

2.3.1 Carbon equivalent value

Carbon Equivalent (CE) is increasingly drawing the attention of the steel making industry since it can have an effect on the properties like strength and weldability in steel bars. In SLS 375 and BS 4449 Standards, the 'maximum percentage by mass' of residual elements is represented by the "Carbon Equivalent" value. The combined effect of carbon with some alloying and residual elements to the strength and weldability of steel is described by the carbon equivalent value. The formula used to calculate the CE is given by Equation (2.1).

$$CE = \%C + \%Mn/6 + (\%Cr + \%Mo + \%V)/5 + (\%Ni + \%Cu)/15 \qquad (2.1)$$

Carbon equivalent (CE) formulae was first developed to provide a numerical value for a steel composition that would give an indication of a carbon content which would cause an equivalent level of hardenability. Later it was extended to represent the contribution of the composition to the hydrogen cracking tendency of steel in welding operations, and also linked to other properties related to hardness, such as toughness and strength.[4]

Table 2.2 presents the contribution made by Carbon Equivalent value to the weldability of TMT bars. [4]

Table 2.2: Weldability of TMT bars based on CE values

Carbon Equivalent (CE)	Weldability of TMT bars
Up to 0.35	Excellent
0.36 – 0.40	Very good
0.41 – 0.45	Good
0.46 – 0.50	Fair
Over 0.50	Poor

Source: Technical Report 1967, IIW Doc. IX-535-67

2.4 Alloying elements

Carbon is the main alloying element in steel with the maximum allowable limit of 0.24% by mass. Carbon is the key contributor to the tensile strength, hardness, weldability and brittleness of steel.

Silicon (Si) in the form of ferro-silicon is added to liquid steel mainly as a de-oxidizer. It removes the undesirable oxygen dissolved in molten steel (Equation (2.2)). Manganese (Mn) can also be used to remove unwanted oxygen in the melt (Equation (2.3)). De-oxidation by Si is however more effective than that by Mn.

$$Si + 2O = SiO_2 \qquad (2.2)$$

$$Mn + O = MnO \qquad (2.3)$$

Manganese is added to liquid steel specially to control its sulphur content. It combines more readily with residual sulphur, to form manganese-sulphide (MnS) (Equation (2.4)).

$$Mn + S = MnS \qquad (2.4)$$

This will reduce the formation of iron-sulphide (FeS), which is a brittle compound that lowers the toughness and ductility of steel and causes hot shortness in it.

Table 2.3 presents a comparison of the properties of Mn and Si as the alloying elements.

Table 2.3: Comparison of Mn and Si used in the steel making process

Manganese (Mn)	Silicon (Si)
An austenite stabilizer	A ferrite stabilizer
Lowers the eutectoid transformation temperature and the eutectoid carbon content	Raises the eutectoid transformation temperature, but lowers the eutectoid carbon content
Cubic structure (bcc). Atomic Radius is 0.112 nm Vanderwaal Radius is 0.126 nm	Diamond cubic structure. Atomic Radius is 0.117 nm Vanderwaal Radius is 0.132 nm
Forms a substitutional solid solution in Fe lattice	Forms a substitutional solid solution in Fe lattice.
Highly effective in strengthening steel. 0.1% addition of Mn to iron will increase the yield strength by 3 MPa	Moderately effective in strengthening steel. Enhances the electrical and magnetic properties

Compared to Cr, both Si and Mn have a relatively potent effect on the hardness of ferrite. Cr increases the hardness only very slightly. Cr, however, is the most convenient alloying element for steel that is processed by cold working for which good hardenability is required. Figure 2.2 shows how the hardness in ferrite is increased by substitutional solid solutions.

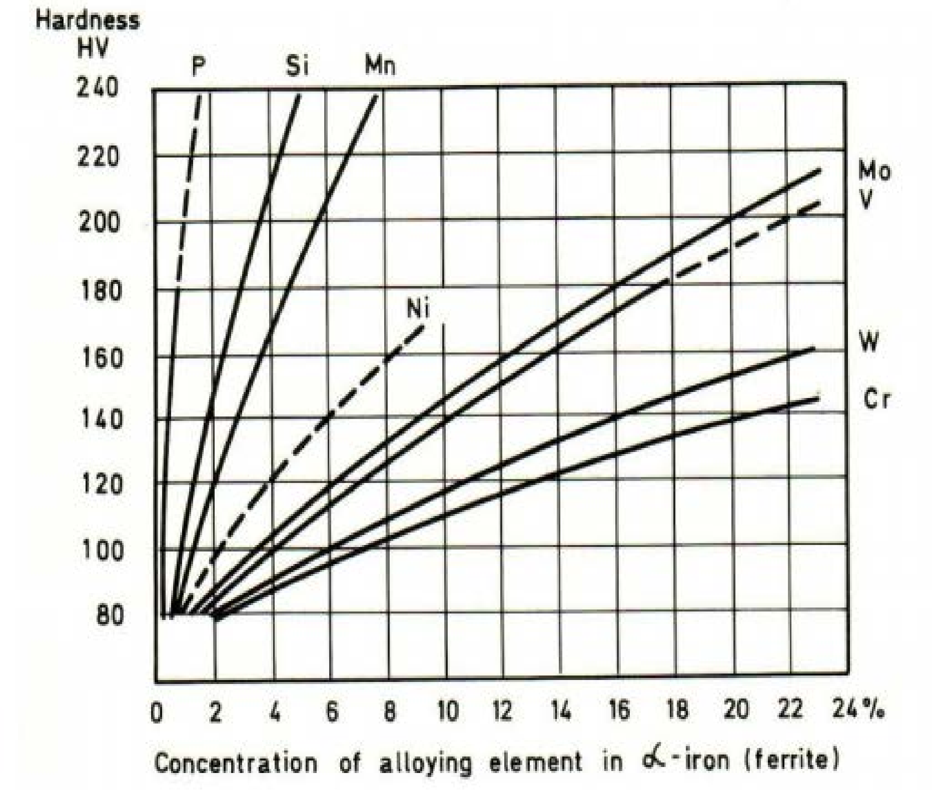

Figure 2.2: Effect of substitutional alloying element additions on ferrite hardness [17].

2.4.1 Solid solution strengthening

Solid solution strengthening is a type of alloying that can be used to improve the strength of a pure metal. Depending on the size of the alloying element used, a substitutional solid solution or an interstitial solid solution can form.

The solid solution strengthening is based on the influence of substitutional atoms which causes stress field in the iron lattice. The solid solution strengthening depends on the concentration of the solute atoms, shear modulus of the solute atoms, size of solute atoms, valency of solute atoms (for ionic materials), and the symmetry of the solute stress field. [15]

Carbon in iron (steel) is one example of interstitial solid solution. Manganese, a metallic alloying element with much larger atoms than carbon, (closer in size to those of iron) forms a substitutional solid solution when added by displacing iron atoms.

Manganese blocks the mechanical movements of the iron lattices and thereby improves the strength and hardness of steel. Silicon can also cause a substitutional solid solution to form by occupying iron lattices. Silicon increases the strength and the hardness of steel although less effective in this regard than manganese. [15]

2.4.2 Solid solution of atoms in iron (Fe) lattice

At atmospheric pressure, there are three allotropic forms of iron: alpha iron (α)-ferrite, gamma iron (γ) - austenite, and delta iron (δ). Iron allotropes, showing the differences in lattice structure. The alpha iron (α) is a body-centered cubic (BCC) and the gamma iron (γ) is a face-centered cubic (FCC).[15]

Figure 2.3 presents an illustration of the allotropy of iron

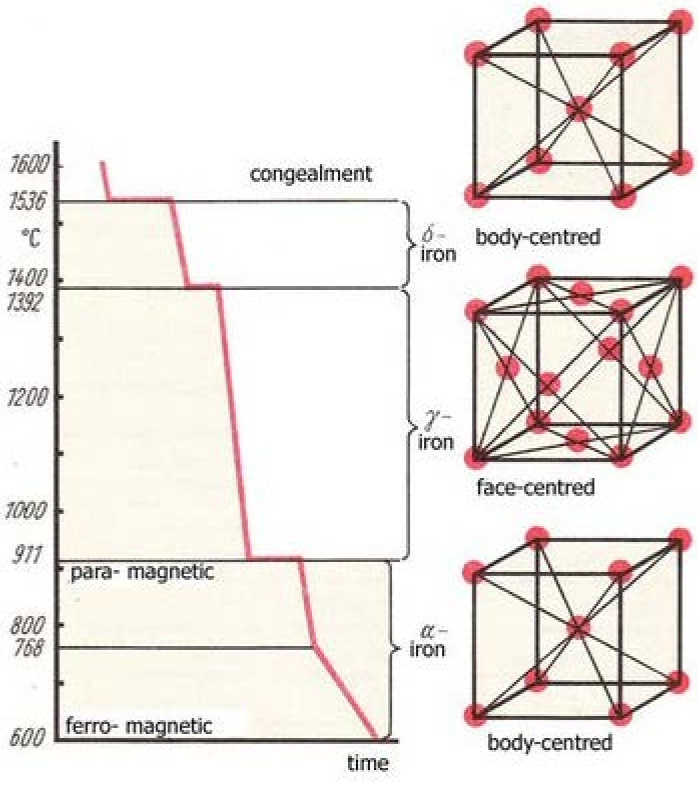

Figure 2.3: An illustration of the allotropy of iron [15]

A substitutional solid solution is one in which the solute atoms of the elements replace those of the solvent atoms in the crystal lattice. An interstitial solid solution is one in which the solute atoms of the elements are positioned in the interstitial spaces between the solvent atoms of the crystal lattice. In both cases, the overall crystal structure is essentially unchanged.

The criteria to be met for the substitutional and interstitial solid solution are as follows:

Substitutional solid solution strengthening occurs when the solute atom is large enough that it can replace solvent atoms in their lattice positions. [15]

1) The difference in atomic radii between the solvent atom (ie. Fe) and the other element (ΔR%) must be less than ±15%,

2) The crystal structures must be the same,

3) The electro-negativities must be similar, and

4) The valences should be the same, or nearly the same.

If the element has atomic radius that is significantly smaller than the atomic radius of solvent atom (ie. Fe), then interstitial solid solution is occurred [15].

2.4.3 Solubility of carbon in iron lattice

Carbon in iron (steel) is one example of interstitial solid solution. It forms a solid solution with α, γ, δ phases of iron. Elements commonly used to form interstitial solid solutions include H, Li, Na, N, C, and O.

Maximum solubility in BCC α-ferrite is limited (max. 0.022 wt% at 727 °C) : BCC has relatively small interstitial positions. Maximum solubility in FCC austenite is 2.14 wt% at 1147 °C : FCC has larger interstitial positions.

Figure 2.4 presents the diagrams of the Unit cells of γ- $_{FCC}$ and α–$_{BCC}$ Fe lattice

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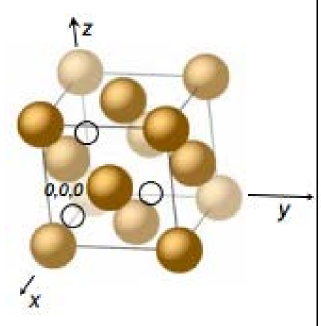
<td>
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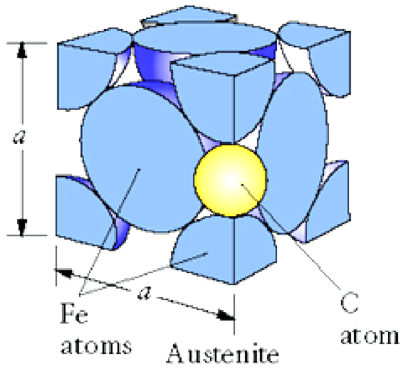
<td>
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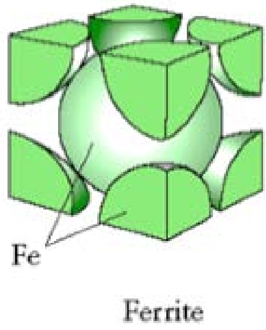
<td>
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<tr>
<td>Interstitial voids in the γ- $_{FCC}$ Fe lattice</td>
<td>Unit cell of γ- $_{FCC}$ Fe lattice</td>
<td>Unit cell of α_{-BCC} Fe lattice</td>
</tr>
</table>

Figure 2.4: Diagrams of the Unit cells of γ- $_{FCC}$ and α_{-BCC} Fe lattice [15]

The BCC structure of α-iron is more loosely packed than that of FCC γ-iron. The largest voids in the BCC structure are the tetrahedral voids existing between two edge and two central atoms in the structure, which together form a tetrahedron.

It is interesting to see that the FCC structure, although more closely-packed, has larger voids than the BCC structure. These voids are at the centers of the cube edges, and are surrounded by six atoms in the form of an octagon, so they are referred to as octahedral holes.

Therefore, the solubility of C in austenite should be greater than in ferrite, because of the larger interstices available.

The atomic diameter of carbon is less than the interstices between iron atoms and the carbon goes into interstitial solid solution of iron. (The atomic radius of Iron (α_{-BCC}) is 0.124 nm and Carbon is 0.091 nm)

2.5 Sponge iron

Sponge iron is a metallic product produced through direct reduction of iron ore in the solid state. It is a substitute for scrap and is mainly used in making steel through the secondary steel production route. Sponge iron is considerably applied for better controlling the carbon content in the melt.

The advantages of sponge iron are as follows:

- It allows steel making to dilute metallic residuals in scrap
- It has a uniform composition
- It has a uniform size
- Sponge Iron has low Sulphur and Phosphorus content as compared to scrap steel

2.5.1 Benchmarking of coal-based sponge iron manufacturing facility

Direct-reduced iron (DRI) or sponge iron is produced from the direct reduction of iron ore (in the form of lumps, pellets or fines) to iron by a reducing gas or elementary carbon produced from natural gas or coal. In DRI production process, solid metallic iron is obtained directly from solid iron ore without subjecting the ore or the metal to fusion.

Since DRI is produced by removing oxygen from iron ore, its structure is like sponge with a network of connecting pores. These pores results in a large internal surface area which is about 10,000 times greater than the internal surface area of solid iron. Due to that, the DRI is also known as Sponge iron. Major DRI production processes are either gas based or coal based.

In a coal based plant, the reactor for the reduction process is an inclined horizontal rotary kiln. In this rotary kiln both coal and the iron ore feed material is charged from the same end of the kiln. During the movement of feed material forward the oxidation reaction of carbon in coal and reduction reaction of CO gas is carefully balanced. A temperature profile ranging from 800-1050 ^{0}C is maintained along the length of the kiln at different zones and as the material flows down due to gravity the ore is reduced.

The reduction reactions in coal based DRI process:

$$C + O_2 = CO_2 \ldots\ldots (2.5)$$

$$CO_2 + C = 2CO \ldots\ldots (2.6)$$

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2 \ldots\ldots (2.7)$$

$$Fe_3O_4 + CO = 3FeO + CO_2 \ldots\ldots (2.8)$$

$$FeO + CO = Fe\ (95\%) + CO_2 \ldots\ldots (2.9)$$

Sponge Iron (Carbon content 0.10 – 0.15 % by mass)

In the coal based process the hot reduced Sponge Iron along with the semi burnt coal is cooled in water cooled cylindrical rotary cooler to a temperature of 100 to 200 ^{0}C. The cooler discharge consisting of Sponge Iron, char and other contaminants is passed through magnetic separators for separating Sponge Iron from other impurities. Gas based DRI is not subjected for any magnetic separation since no contamination with non magnetic is possible. The gas based DRI is either cooled indirectly or used in hot condition.

Figure 2.5 shows some photographs of the horizontal Kiln used to manufacture iron pellets from the iron ore.

Figure 2.5: Photographs of the horizontal Kiln used to manufacture sponge iron

Figure 2.6 shows the photographs of the samples of iron ore and iron pellets (Sponge iron) taken during the plant visit.

Iron ore sample

Iron pellet (Sponge iron) sample

Figure 2.6: Photographs of the samples of iron ore and iron pellets

2.6 Secondary steel manufacturing process

Primary steelmaking is described as a fast melting and rapid refining process. Primary Steel making is capable of refining at a macro level as per broad specifications, but is not designed to meet the stringent demands on steel quality and consistency of chemical composition. In order to meet the requirements for very sophisticated grades of steel, liquid steel from primary steelmaking units has to be further refined in the ladle after tapping. This is known as "Secondary Steel making".

Secondary Steelmaking is aimed to achieve one or more of the following requirements: [14]

- Improvement in Quality
- Improvement in production rate (productivity)
- Higher recovery of alloying elements
- Use of relatively cheaper grades of raw materials
- Decrease in energy consumption
- Use of alternate sources of energy

Figure 2.7 presents a schematic illustration of the main iron and steel production routes.

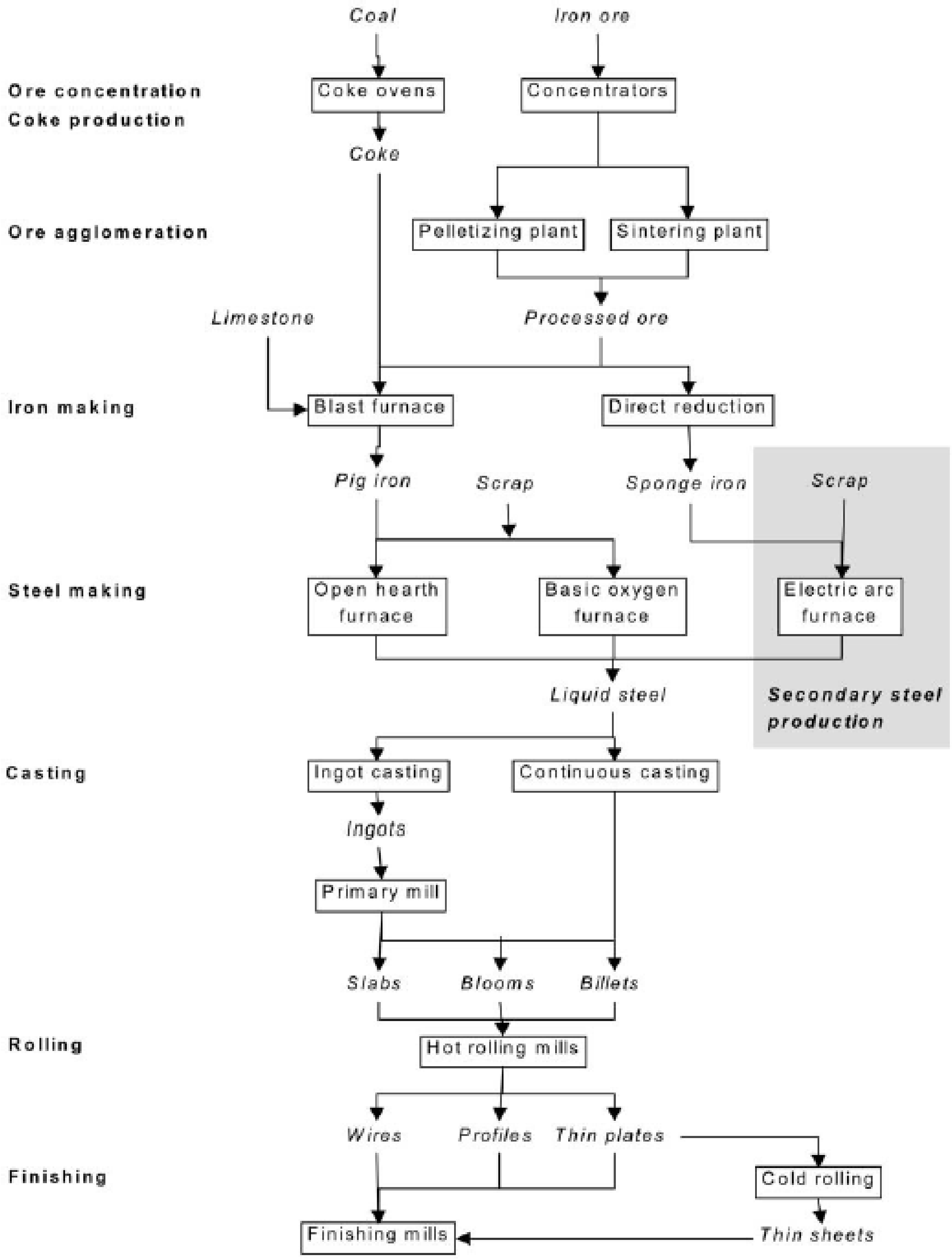


Figure 2.7: Schematic illustration of the main Iron and Steel production routes (Source: WEC, 1995)

2.7 Use of induction furnace and metallurgical aspects in steel making

Steels of high quality are made in Electric Furnace. Electrical Arc Furnace is the best choice for melting process, but due to the high energy consumption Bottom pouring induction furnaces are widely used by the steel manufacturers. [5]

The ingot stage of Steel production has great influence on the properties and characteristics of the finished bars. Blowholes, Surface imperfections and Segregation of alloy constituents tend to persist and those will affect the strength of the reinforcement bars.

Dissolved oxygen is removed from the liquid steel by adding appropriate content of Silicon and Manganese (Deoxidizers). They combine with the dissolved oxygen, forming solid oxide products which remain as minor inclusion in the steel, no dissolved oxygen remains to form blowholes. Deoxidizers can be added while the steel is still in the melting furnace or to the ladle of steel, as it is tapped from the furnace for the ingot mould.

When the heat of steel is completed, the furnace is tapped to pour the melt into ladle, from which it is poured into ingot moulds to solidify. The moulds are generally made out of cast iron, with thick walled and open at both ends. Pouring may be 'Top or Bottom' pouring. The cross-sectional shape may be square or rectangular. During solidification, metal first begins to freeze at the mould wall (Heterogeneous nucleation). Freezing progresses with a thickening of solid by an inward growth of columnar dendritic crystals. Corrugations or flutes are often provided on ingot mould walls to accelerate cooling, to minimize the formation of long parallel crystals and to ensure a finer grain structure. [5]

After the ingot has completely solidified, it is removed from the mould and prepared for further processing. These ingots are reheated to a uniform temperature for the hot rolling.

2.8 Continuous casting process

The advantages of continuous casting of steel billets can be summarized as follows [14]:

- It is directly possible to cast various slabs, blooms and billets to a large extent, eliminating the blooming, slabbing mills completely.
- Improved quality of the cast products
- Higher crude-to-finished steel yield (about 10 to 20% more than ingot casting)
- Higher extent of process control and automation.

2.8.1 Metallurgical comparison of continuous casting with ingot casting

- The surface area-to-volume ratio per unit length of continuously casted ingot/ billet is larger than that for typical ingot casting. As a consequence, the linear rate of solidification (dx/dt) is an order of magnitude higher than that in ingot casting.
- The dendrite arm spacing in continuously cast products is smaller compared with that in ingot casting.
- Macro-segregation is less, and is restricted to the centerline zone only.
- Endogenous inclusions are smaller in size, since they get lesser time to grow. Thereby, the blow holes (on an average) are smaller in size.
- Inclusions get lesser time to float-up. Therefore, any non-metallic particle coming into the melt at later stages tends to remain entrapped in the cast product.
- Continuously cast billet is very long. Hence, the heat flow is essentially in the transverse direction, and there is no end-effect as is the case in typical ingot casting. (ex. Pipe at the top, bottom cone of negative segregation, etc.)
- The depth of the liquid metal pool is several metres long. Thereby, the ferro-static pressure of the liquid is high during the latter stages of solidification, resulting in significant difficulties for the formation of blow-holes.

Figure 2.8 shows some photographs of the continuous casting of steel billets taken at the plant visit.

Figure 2.8: Photographs of the continuous casting of billets

2.8.2 Major types of casting imperfections

Classification and designation of all possible casting imperfections [3] are as follows:

1. Metallic Projections:
    - ❖ Metallic projections in the form of Fins or Flash
    - ❖ Swells: Excess metal on the external or internal surfaces of the castings
2. Cavities:
    - ❖ Blowholes, Pinholes:

      During solidification of metals in an ingot mould, much of the gas is removed in the form of bubbles. Those gas bubbles are trapped within the solid ingots and called as "blowholes" (internal porosity).
    - ❖ Cavities with generally rough walls, shrinkage
    - ❖ Porous structures caused by numerous small cavities
3. Discontinuities:
    - ❖ Cracks and Tears (discontinuities caused by internal tension, lack of fusion, metallurgical defects)

4. Imperfect Surfaces:
    - ❖ Casting surface irregularities
    - ❖ Serious surface defects
5. Incomplete Castings:
    - ❖ Missing portion of casting
6. Incorrect Dimensions or Shape:
    - ❖ Casting shape incorrect overall or in certain locations
7. Inclusions or Structural anomalies
    - ❖ Inclusions
    - ❖ Structural anomalies visible by macroscopic observation

2.9 Specifications for quality of rebars for the reinforcement of concrete

Many countries have published standard specifications for ribbed steel bars to ensure their quality when used in their intended purposes. In Sri Lanka, SLS 375: 2009 (Specification for ribbed steel bars for the reinforcement of concrete) ensures the quality of ribbed steel bars when used as reinforcements in concrete. [4]

As per SLS 375: 2009 standard, the chemical composition of ribbed steel bars, based on its product analysis shall be in accordance with the figures given in Table 2.4.

Table 2.4: Chemical composition of ribbed steel bars (maximum % by mass)

	C	S	P	N	Cu	*CE
Cast analysis	0.22	0.05	0.05	0.012	0.80	0.50
Product analysis	0.24	0.055	0.055	0.014	0.85	0.52

Source: SLS 375: 2009 – *Specification for ribbed steel bars for the reinforcement of concrete*

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$$

2.10 Optimizing the parameters of water quenching process

The controlling parameters such as water pressure, rolling speed, cooling rate and finished rolling temperature of bars have to be controlled to improve the yield strength of bar produced. The yield strength is highly depended on the cooling rate. Therefore, selecting the most appropriate type of cooling system (economically feasible) is a must for desired yield strength. [2]

There are three types of cooling systems used in hot rolling:

- Water jet cooling system
- Water spray cooling system
- Mist cooling system

Design of Experiment (DOE) by Taguchi method of orthogonal array can be applied to robust parameter design for cooling system and to find the effect of those parameters on yield strength of TMT bars. As per the DOE by Taguchi method, water pressure has shown the highest impact over the yield strength of TMT bars. [2]

2.11 Thermo-mechanically treated (TMT) bars

TMT bars are extra high strength reinforcing bars, which eliminate any form of cold twisting. In TMT, property changed due to a change in the internal structure of steel.

During TMT bar manufacturing process, the steel bars receive a short intensive cooling when they pass through a water cooling system. The sudden reduction in temperature converts the surface layer of the bar into a hardened structure. This phase of intensive cooling is followed by cooling in atmosphere, so that the temperature of the hot core and the temperature of the cooled surface is equalized. Therefore the surface layer gets tempered by the heat from the core of the bar. The resulting structure is a tempered Martensite zone at the periphery and a fine grain Ferrite-Pearlite structure in the central zone. Hence, TMT bars posses improved properties of high strength combined with toughness and ductility [10].

TMT bars are more ductile compared to CTD bars. The unique feature of TMT bars is their high fatigue resistance on dynamic loading on account of the high strength of the surface layer. TMT bars have high percentage of uniform elongation, thus high formability. Figure 2.9 represents the structural changes in steel due to different cooling rates.

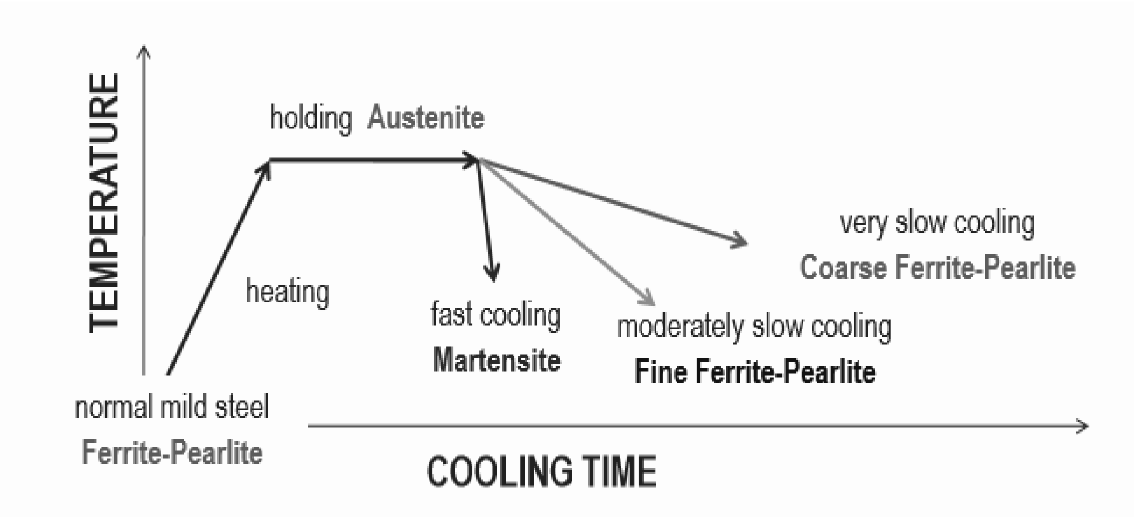


Figure 2.9: Structural changes in steel on different cooling rates [10]

2.11.1 Fundamental mechanisms of the QTB process

Figure 2.10 shows the typical cooling and reheating curves of the surface, center and midway point of the bar. The figure also shows the microstructure before quenching, after quenching and after tempering.

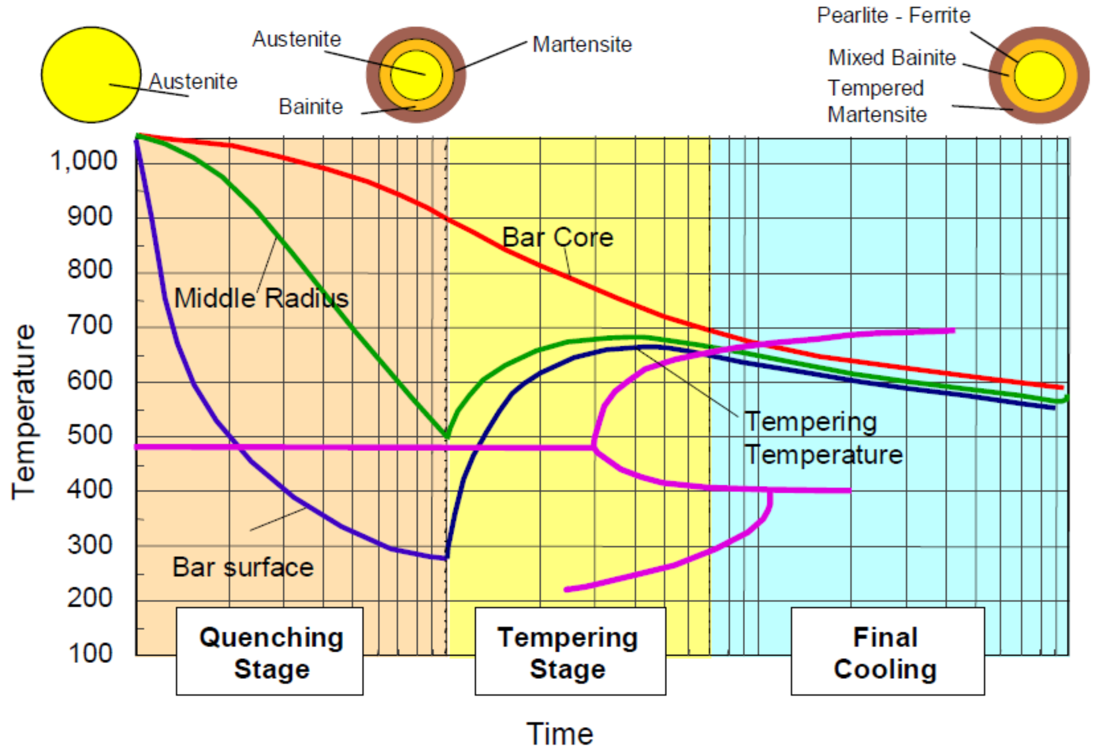


Figure 2.10: Thermal path of the QTB process [18]

Main stages of the QTB process are as follows:

01. Quenching Stage

At this stage, Steel bars receive a short intensive cooling when they pass through the water cooling system. The efficiency of the cooling system has to be good enough to quench the bar surface faster than the critical cooling rate for Martensite formation. At the end of the quenching stage, the bar microstructure is changed from fully Austenitic structure into a 3-phase structure as follows.

- Surface layer of the bar - Martensite
- Intermediate annular area - Mixture of Austenite, Bainite and Martensite
- Inner Core - Austenite

The core temperature of the bar has to be maintained in the Austenitic temperature range in order to obtain a subsequent Ferrite-Pearlitic transformation during the next stages.

02. Tempering Stage

During the self-tempering stage, the bar is naturally cooled in air. The heat flux from the hot core re-heats the quenched surface by heat conduction, and thereby the already formed Martensite layer is self-tempered, thus giving sufficient ductility to the bar. At the end of the Tempering Stage, the bar microstructure is changed as follows

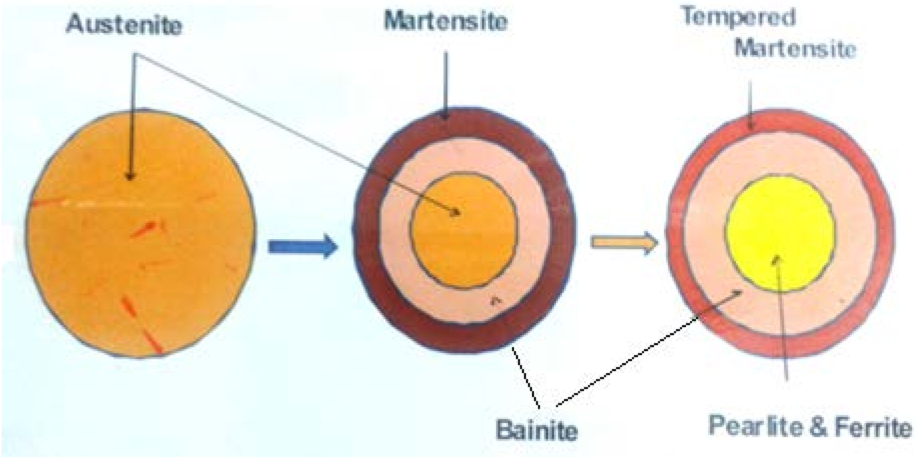
- Surface layer of the bar - Tempered Martensite
- Intermediate annular area - Mixture of Bainite, Austenite and some tempered Martensite
- Inner Core - Starts to transform from Austenite structure

03. Final Cooling Stage

Final cooling stage begins when the bar has been transferred to the cooling bed and thereby a quasi-isothermal transformation occurs and the microstructure of the core is changed from the Austenitic structure into a Ferrite-Pearlitic structure.

The 'Tempering temperature' is the maximum surface temperature achieved at the end of the second stage (Tempering stage) and it is totally depending on the quenching rate during the first stage. The longer the quenching stage, the deeper the Martensite layer, the lower the bar temperature at the end of the quenching stage, and the lower the tempering temperature as well. [18]

Quenched and Self Tempered steel bar has Ferrite-Pearlite structure at the core and tempered Martensite at the surface. Hence, the bar with a hard surface and a soft/ ductile core will increase the yield strength. Figure 2.11 represents the cross sections of the transformed bars.



Re-heated bar Quenched bar Quenched and Tempered bar

Figure 2.11: Schematic representation of the transformed bars [18]

Microstructure of the cross section of a TMT bar was observed by etching a polished cut-end in Nital (a mixture of nitric acid and methanol), as shown in Figure 2.12. Three distinct rings appeared when the cut end of a TMT bar was etched in Nital.

Figure 2.12: Photographs of the cross section of a TMT bar

2.11.2 Microstructure of the distinct layers of a TMT bar

The microstructure of the surface layer, annular zone and core zone of a TMT bar is represented in figure 2.13.

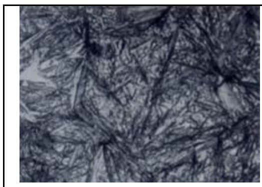
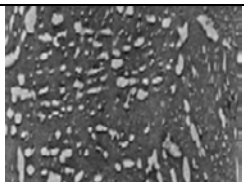
	 Surface Layer	 Annular Zone	 Core Zone
Martensite (needles/ black) Non Equilibrium Structure Extremely hard and brittle	**Tempered Martensite** Tough (Reduced hardness and brittleness and increased ductility) Depth 0.8 – 2.0 mm/ Hardness 280 – 300 HV	**Mixed Bainite** Depth 1.2 – 2.8 mm/ Hardness 220 – 240 HV	**Pearlite – Ferrite** Hardness 190 – 210 HV

Figure 2.13: Microstructure of the distinct layers of TMT bar [18]

The Austenite transformtions on different cooling rates can be summarized as shown in figure 2.14.

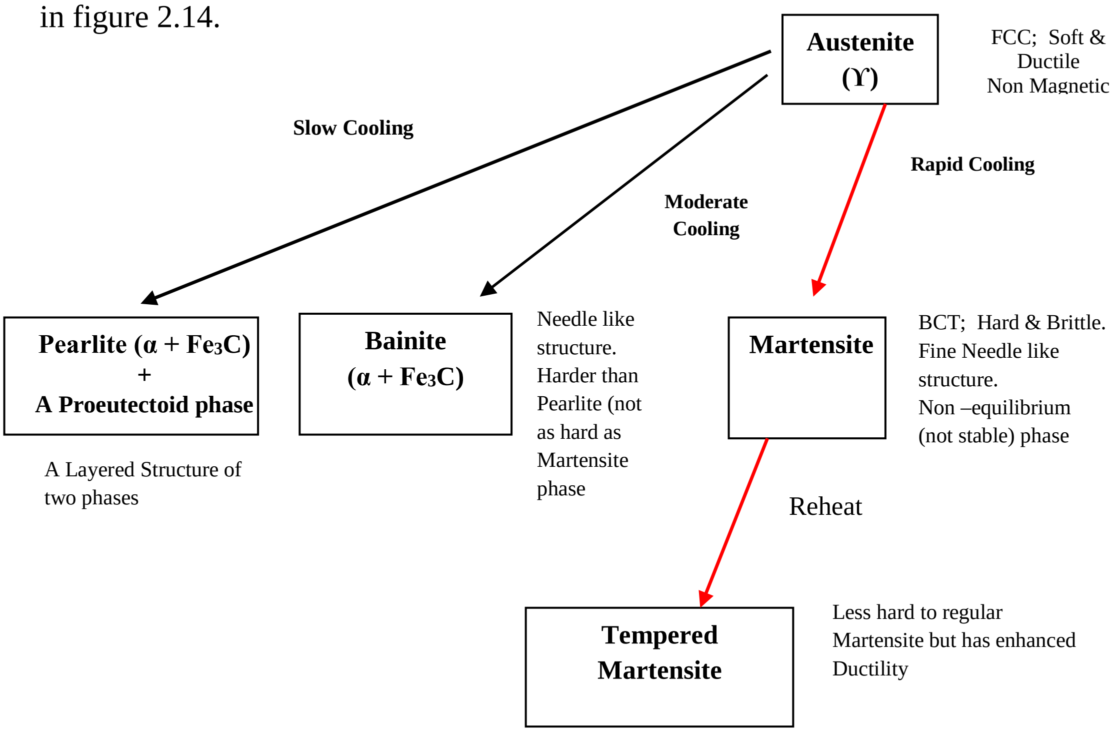


Figure 2.14: Austenite transformtions on different cooling rates [18]

2.12 Effect of corrosion of the TMT bars

Corrosion of steel reinforcement leads to cracking of reinforced concrete sections and thus may further reduce the load carrying capacity and serviceability of the concrete structures.[7]

Corrosion of rebars may cause reduction in yield strength of steel, affect the bond strength due to de-lamination of rust formed on the rebar surface.

The yield strength of steel bars is not affected at a lower percentage of corrosion, but for higher percentage of corrosion there is a considerable reduction in yield strength and percentage of elongation.

Also revealed that, at a higher percentage of corrosion the failure pattern of bars had changed from ductile mode to brittle mode.

CHAPTER 03

METHODOLOGY

3.1 Introduction

This research depended on both qualitative and quantitative information obtained through the onsite surveys conducted among metallurgists in the recycling plants. Ample time was spent on the production floor to study about the operational control activities in ingot casting and quenching operations. Improvement suggestions were made using the knowledge gained from the literature review as well as the observation and experience through benchmarking of best practices.

The scope of research was limited to the rebar of size 10 mm. Improving of key control parameters of the water quenching process was completed as a part of the research component. The experimental study was focused on identifying the most suitable mixed proportion of ferro-silicon to ferro-silico-manganese, and the best controllable range of CE values to be used during melting to ensure that the products manufactured are consistent in quality. The quantities of the main alloying chemicals mixed together are changed to make the diluted percentage of manganese content in the bath solution to be 0.8% by mass.

The ingots and TMT bar samples prepared in 19 consecutive charges were tested to see how the mixed proportion of alloying chemicals and the Carbon Equivalent value affect the variation in yield strength and elongation of the finished bars.

The test data of the respective samples were analyzed using Matlab and Microsoft Excel, and the graphs in both second order polynomial (quadratic form) and third order polynomial (cubic form) were created using Minitab.

3.2 Onsite survey on operational control activities

In-depth investigation was carried out at the steel plant covering the process control activities relevant to the casting of ingots and quenching processes to see whether there exist any rooms for improvement.

3.2.1 Operational control activities of melting and casting processes

- Furnace inspections shall be carried out for proper lining. Lining is done with Ramming Mass, Boric acid and Sodium Silicate.
- Charging the furnace with end cuttings (small scrap) and super melting materials at first.
- Removal of slag from the liquid solution has to be done while charging the metal scraps.
- Some disposable types of probes are used to collect the bath samples for chemical testing.
- Sponge iron is considerably applied for better controlling the carbon content in the melt.
- Addition of alloying chemicals to correct the chemistry in the liquid steel is to be done in careful manner.

  If the C percentage is more than the required level, then it shall be boiled down (oxidation) using mill scale. If it is less than the requirement, then Coke (70% of fixed carbon) shall be added to the melt.

  Ferro-silicon (Si : 70% by mass) and Ferro-silico-manganese (Mn : 60% and Si : 14% by mass) are the main alloying chemicals mixing to the liquid steel. The quantities of ferro-silicon and ferro-silico-manganese allocated to a charge-mix are found to be 7.5 kg and 48 kg respectively. (Furnace capacity is nearly five metric ton of liquid metal)

- Once the heat of liquid steel is completed (1500^0C – 1600 ^{0}C), the furnace is tapped to pour the melt into the ladle, from which it is poured into ingot moulds to solidify.

- After completing the solidification stage, ingots are removed from the moulds and prepared for further processing. These ingots are reheated to a uniform temperature for the hot rolling process.

Figure 3.1 shows some photographs relevant to the ingot casting process at the steel plant.

Scrap melting | Tapping process | Bottom pouring structure | Steel ingots

Figure 3.1: Photographs relevant to ingot casting process

3.2.2 Operational control activities of the quenching process

- Selecting the TMT nozzle in accordance with the nominal diameter of the bar to be produced.
- Setting the cooling water temperature in between 30 ^{0}C – 40 ^{0}C
- Passing a sample bar (trial run) through the quenching box to verify the temperature readings of the hot and cold bar and cold water respectively.
- Applying the water pressure and flow rate by adjusting the valve positions of bypass valve so that the yield strength of the sample is reached to a level in the specified range of 500 N/ mm^2 to 650 N/mm^2
- Sustaining the cooling parameters till the completion of entire batch
- After finishing the quenching treatment (550^0 C – 650^0 C) bars are kept on the cooling bed for self-tempering under natural cooling.

Figure 3.2 shows the layout of water quenching box at the steel plant.

Figure 3.2: Photographs of the water quenching process

3.2.3 Improvement suggestions identified by the survey

1. Uniformity of test results of the YS and elongation of a TMT bar sample can be achieved to some extent by improving the key parameters of the quenching process

2. Variation in YS and elongation can be further reduced by changing the mix-quantities of the main alloying chemicals to make the diluted percentage of manganese content in the bath solution to be 0.8% by mass.

3.3 Experimental works

3.3.1 Improving the key parameters of the quenching process

The water quenching process was improved by controlling key parameters as a part of the research component (to reduce the variation in yield strength and elongation up to certain extent).

The parameters such as cooling water pressure (kg/mm^2), water flow rate (m^3/h), bar speed (m/s) and end-quench temperature of the bar are the key factors that affecting the yield strength and elongation of the TMT bars. It was realized that water pressure and the flow rate are the most significant parameters to be controlled at utmost concern.

The process improvement was made through the correct adjustment of water pressure and the flow rate, in accordance with the bar size, rolling speed, and end-quench temperature. Tremendous efforts were made through number of trails runs to establish an improved parameter set-up for the quenching operation so that the yield strength of the TMT bars in a set is reached to a value in the range of 530 N/mm^2 to 600 N/mm^2. (Appendix 02: Trial runs)

In accordance with the bar size, the most suitable levels for the inlet water pressure and the flow rate were determined as presented in Table 4.2 in Chapter 04.

A conformity test was performed for three nominal sizes after the improved control factor setting was determined. (Appendix 04)

3.3.2 Improving the ingot casting operation

In the experimental work, the mixing quantities of the main alloying chemicals were changed to ensure that the diluted percentage of the manganese content in the liquid solution was 0.8% by mass. A mix-proportion of ferro-silicon and ferro-silico-manganese which was determined considering product specifications and past experience in trial mixes was added to a number of charges during the melting process.

Seventy kilograms of ferro-silico-manganese (Mn: 60% and Si:14% by mass) were added to the melt of 5 metric tons. The quantities of manganese and silicon added were 42 kg and 9.8 kg respectively. Additionally, 2 kg of ferro-silicon (Si: 70% by mass) were added to the melt just before tapping, and 1.4 kg of silicon obtained. The total amount of silicon added to the melt was 11.2 kg. Thereby, the mixed proportion of silicon to manganese in the melt was 1 is to 4 approximately.

3.3.3 Sampling

Before rolling the prepared ingots into bars, ingot samples were collected from 19 different charges for chemical analysis.

After manufacturing 10 mm TMT bars using the ingots of the identified charge numbers, a set of TMT bar samples was drawn for testing their yield strengths and elongations.

Table 3.1 shows the respective details of the samples drawn for testing.

Table 3.1: Details of the samples used in the research

Serial number	Charge number or Batch number	Number of Ingot pieces for chemical analysis	Number of TMT bars for physical testing (size 10 mm)	Total length of the test piece (m)
1	16/07/01/01	01	05	1
2	16/07/02/02	01	05	1
3	16/07/04/03	01	05	1
4	16/07/05/04	01	05	1
5	16/07/13/03	01	05	1
6	16/07/14/04	01	05	1
7	16/07/30/05	01	05	1
8	16/08/03/03	01	05	1
9	16/08/04/04	01	05	1
10	16/08/05/05	01	05	1
11	16/08/06/01	01	05	1
12	16/08/08/02	01	05	1
13	16/08/09/03	01	05	1
14	16/08/10/04	01	05	1
15	16/08/12/06	01	05	1
16	16/08/19/07	01	05	1
17	16/08/20/08	01	05	1
18	16/08/29/06	01	05	1
19	16/08/30/07	01	05	1

3.3.4 Testing

Chemical analysis of the ingot samples was carried out using the Spectro Spark Analyzer that was available at the steel plant. Because of its rapid analysis time and inherent accuracy, the Spectro Spark Analyzer is more effective in controlling the processing of alloys and residuals. The data used in this study for the spectrometer analysis are given in Appendix 05.

Tensile testing of the TMT bar samples was carried out using the Universal Testing Machine (UTM) that was also available at the steel plant. All the specimens were tested without any machining and in accordance with the SLS 375: 2009 standard. The test data obtained are given in detail in Appendix 06.

Figure 3.3 shows the Spectro spark analyzer and the Universal Testing Machine available at the steel plant.

Figure 3.3: Photographs of the Spectro Spark Analyzer and the UTM

3.3.5 Apparatus used and calibration status

The following apparatus were used during this research to carry out the testing and measurements.

1. Universal Testing Machines (UTM):

   Brand Name : Kristal,

   Model no : UTK 60

   Capacity/ Max Load : 600 kN

2. The SPECTROMAX stationary metal spark analyzer

   The least count is 0.01% (i.e 0.0001).

3. Vernier Caliper

   The least count is 0.01 mm

4. Electronic Weighing Scale

   The least count is 0.01 g

5. Infrared Pyrometers (Non contact Thermometer)

   Measuring range is over 530 ^{0}C (1000 ^{0}F) up to 3000 ^{0}C (measurement error of +/- 2^{0}C). Only the surface temperature of the hot metal can be measured.

6. Water flow meters (Digital)
   Least count is 1 m^3/h

7. Pressure Gauges

   Least count is 0.5 kg/cm^2

The calibration status of all testing equipment was assessed to see the accuracy of measurement. Universal testing machine, Vernier caliper, electronic weighing balance, thermo couples, water flow meters and pressure gauges are calibrated annually by a reputable party to ensure that errors associated with the measurements are in the acceptable range.

Certified reference materials are used as standard kits for calibrating the Spectrophotometer and it is verified at every time prior to analyze the test piece.

3.3.6 Analysis of test data

The test results of nineteen charges were analyzed using Matlab and Microsoft Excel, to assess the standard deviations of yield strength for the mixed proportions as presented in Table 4.1 in Chapter 04.

A statistical analysis in terms of R^2 values was conducted using Minitab to identify the curves that best fit the data set. The graphs created in second order polynomials (quadratic form) and third order polynomials (cubic form) were assessed to see the level of fitness to the data set. When interpreting the R^2 values, it was observed that the plots in cubic form are more fitting than the plots in the quadratic form. (Appendix 07- the plots in the quadratic form)

Therefore, the cubic model was used to explain how the standard deviations of the yield strength and elongation are varied as per the different CE values, as shown in Figure 4.1 and Figure 4.2 in Chapter 04.

CHAPTER 04

RESULTS AND DISCUSSION

4.1 Mixed proportion of alloying chemicals

For the mixed proportions of Si to Mn given in Table 4.1, a very low value for the standard deviation of yield strength was observed with ferro-silicon and ferro-silico-manganese mixed at the proportion of 1 : 4 (Si : Mn) approximately.

It was also observed that STD-YS changes when the mixed proportion is changed.

Table 4.1: Analysis of the mixed proportions of Si to Mn

#	C	Mn	Si	Yield Strength (YS)	STD-YS	Mn/ Si
1	0.177	0.725	0.161	559.30	10.41	4.5
2	0.196	0.793	0.213	552.38	8.34	3.7
3	0.169	0.817	0.177	549.15	13.82	4.6
4	0.192	0.725	0.210	561.61	7.43	3.5
5	0.190	0.919	0.214	551.27	14.28	4.3
6	0.193	0.854	0.219	560.99	7.07	3.9
7	0.186	0.845	0.178	547.40	10.09	4.7
8	0.189	0.814	0.221	522.59	6.17	3.7
9	0.183	0.821	0.209	509.54	6.33	3.9
10	0.200	0.844	0.172	522.30	16.62	4.9
11	0.179	0.826	0.196	536.37	7.26	4.2
12	0.196	0.910	0.144	558.73	10.95	6.3
13	0.196	0.847	0.205	546.12	12.42	4.1
14	0.198	0.915	0.189	541.23	11.43	4.8
15	0.202	0.759	0.207	527.27	7.77	3.7
16	0.185	0.751	0.197	527.18	11.47	3.8
17	0.201	0.798	0.218	516.39	6.67	3.7
18	0.189	0.822	0.196	562.52	7.54	4.2
19	0.201	0.872	0.187	522.28	15.32	4.7

De-oxidation is one of the most important stages in steel making. The steel bath at the time of tapping contains 400 to 800 ppm activity of oxygen. De-oxidation is carried out during tapping by adding appropriate amounts of ferro alloys or special de-oxidizers to the steel. Ferro-silico-manganese is added as a desulphurizing agent as well as a de-oxidizer. Ferro-silicon is mainly a de-oxidizer of molten steel. De-oxidation by Si is more complete than that by Mn, and simultaneous de-oxidation by these two elements gives rise to a lower residual oxygen content in the bath solution. Depending on the concentration of Si and Mn added to the molten steel, de-oxidation product will be either in molten manganese silicate ($MnO.SiO_2$) or solid silica (SiO_2). In addition to its use in the production of steel ingots to eliminate blowholes, de-oxidation is also employed for grain size controlling that will enhance the strength and toughness of steel.

Manganese (Mn) is the most prevalent alloying agent in steel, second to carbon (C). The increase in the strength and hardenability of steel obtained by using Mn is somewhat less than that obtained by using C. Mn improves hot workability of steel by preventing the formation of low melting iron sulphide (FeS). Another important feature of Mn is its ability to stabilize the austenite content in steel. Mn helps to lower the temperature at which austenite transforms into ferrite, thus avoiding cementite precipitation at ferrite grain boundaries. Mn addition promotes finer grain sizes to strengthen the steel. There is no satisfactory substitute for Mn in the steel making industry given its relatively low cost and outstanding technical benefits.

Silicon (Si) is used mainly as a de-oxidizer in the steel making process. It slightly increases the strength of ferrite, and when used in conjunction with manganese can help to increase the strength and toughness of steel.

The yield strength increase of steel will depend on the concentration of solute atoms in the iron lattices. However, the industry standards limit the maximum possible solubility of alloying elements, in order to prevent the formation of hard and brittle phases.

Manganese content cannot be increased unduly, as it can become harmful. Mn is specified in low carbon steels in the range up to 1 % by mass. A high manganese content will increase the formation of martensite in steel and thereby its hardness and will also raise its ductile to brittle transition temperature. Increased amounts of de-oxidizers that are stronger than Mn such as silicon (Si) or aluminium (Al) can cause Mn to transfer from slag to metal. A high content of Si in low carbon steels is detrimental to surface quality. Therefore, the most appropriate mixed proportion of the alloying chemicals that can be used in the secondary steel making process has to be decided carefully to avoid these undesirable effects.

According to the results of the experimental study, very precise and accurate results on yield strength can be obtained by setting the mixed proportion of Si to Mn at approximately 1 is to 4.

4.2 Carbon equivalent value for improved quality

A graphical analysis was carried out to see how the CE value can be controlled to reduce the standard deviations of yield strength and elongation, while preserving weldability of TMT bars.

In the two graphs given in Figure 4.1 and Figure 4.2, standard parameters S (Standard error of the regression), R^2 (coefficient of determination) and 'adjusted R^2' are used to explain how well the model fits the data set. S which is measured in the same units as the response variable represents the average distance that the data values fall from the regression line/ curve. Smaller S values are better because then the observations will be closer to the fitted line. R^2 value gives the proportion of variance in the dependent variable that can be explained by the independent variables. The predictions are much more precise at high R^2 values. Low R^2 values will be problematic when precise predictions are needed.

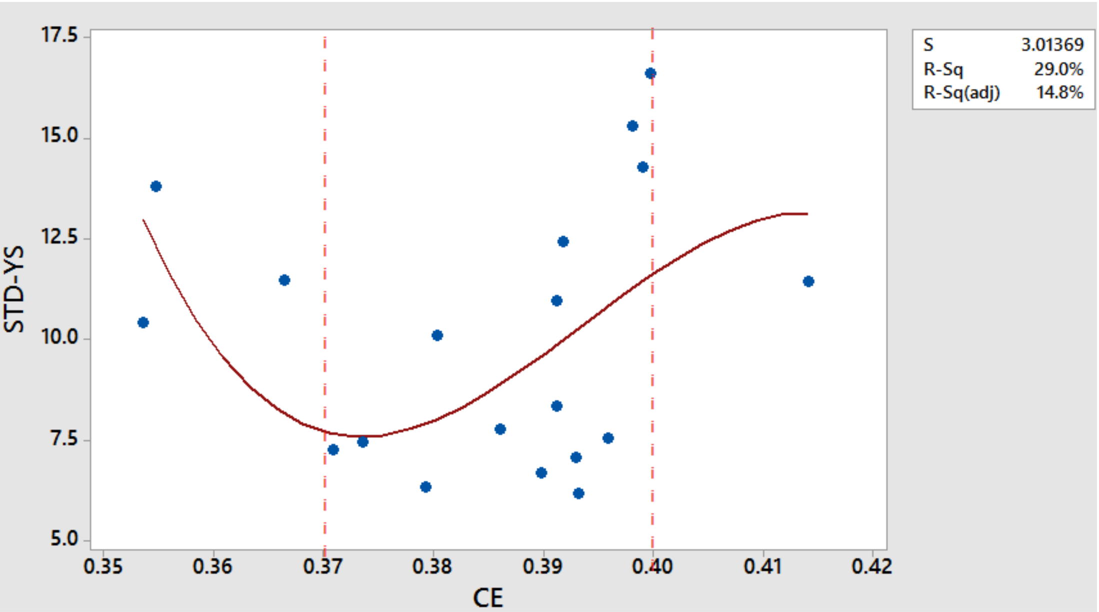


Figure 4.1: Fitted line plot in cubic form (CE vs. STD-YS)

For the interpretation of data in Figure 4.1, S is 3.01369 units of STD-YS. Additionally, 29.0% of the variation in STD-YS is explained by CE.

In the curve of “CE vs. STD-YS” given in Figure 4.1, most of the standard deviations of the yield strength were observed to be quite low for CE values falling in the range 0.37<CE< 0.4 % by mass. Outside this range, the yield strengths are found to vary very much.

This implies that, within that given range of CE values, each and every bar in the lot would have a uniform yield strength, with the variation among the bars at a very low value. The most probable reason for this behaviour of the TMT bars could be the presence of an accurate concentration of Mn in the steel.

It is evident that, C and Mn are the main contributors for increasing the CE value when compared with the weightages of other residuals. The grain size refinement caused by the addition of Mn strengthens steel. The yield strength is increased as the grain size is reduced (ferrite, bainite, or pearlite). In addition, for a given C content the pearlite content will increase as the Mn concentration is increased with the yield strengths of the steel bars also increasing uniformly.

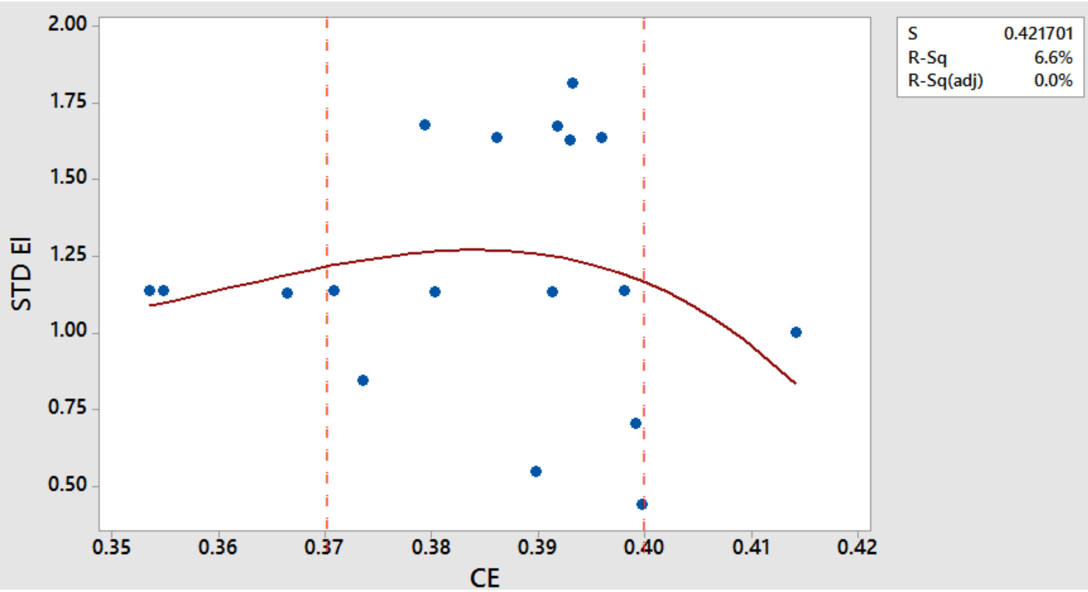


Figure 4.2: Fitted line plot in cubic form (CE vs. STD- Elongation)

For the interpretation of data in Figure 4.2, S is 0.421701 units of STD-El. Additionally, 6.6 % of the variation in STD-El is explained by CE.

Unlike in the curve of “CE vs. STD-YS” plotted in Figure 4.1, in the “CE vs. STD-El” curve plotted in Figure 4.2, the range of CE values over which the standard deviation of elongation remains low is not significant. However, it was noted that the standard deviation of elongation (STD-El) is decreased (in a downward trend) as the CE value is increased.

The higher the CE value, the higher will be the tendency for the strength of steel to increase. Then each TMT bar will gain strength and hardness equally. For this reason, the standard deviation of elongation of the individual bars decreases as the CE values is increased.

From the graphical analysis, it is revealed that consistent values of yield strength and elongation can be achieved (while preserving the weldability) for the set of TMT bars by having the Carbon Equivalent value in the range $0.37<CE< 0.4$ % by mass.

4.3 Improved parameter set-up of the quenching process

Table 4.2 presents the improved parameter set up of the TMT box.

Table 4.2: Improved parameter set-up for water pressure and flow rate

Nominal Diameter	Water Pressure (kg/cm^2)	Water Flow rate (m^3/h)
10 mm	9 - 10	90 - 110
12 mm	10 - 11	125 - 145
16 mm	11 - 12	230 - 250
20 mm	12 - 13	190 - 210 *
25 mm	13 - 15	230 - 250 *

(*Single nozzle is used for quenching the sizes of 20 mm & 25 mm)

Bar Speed : 4.76 m/s
Finish Rolling Temperature of the Bars : 550^0C – 650^0C
Cooling water Temperature : 30^0C – 40^0C

Table 4.3 represents the result of the conformity test performed for the nominal size 10 mm after the improved control factor setting was determined.

Table 4.3: Conformity test results of size 10 mm TMT bar sample.

Parameter	Steel grade RB 500					SLS 375: 2009 Standard Specification (*size 10 mm*)
	Specimen number					
	01	02	03	04	05	
Mass per metre (kg/m)	0.614	0.602	0.600	0.611	0.600	0.588-0.644
Yield Strength (R_e) N/mm^2						650 > YS > 500
Individual	593.5	595.2	593.4	595.5	573.8	
Mean value $\bar{x}$	590.2					
Standard deviation [s]	9.2					
$\bar{x}$ - ks (k=1.53)	576					
Total elongation at maximum force (A_{gt}) %						(> 2.5)
Individual	6.24	7.74	8.34	6.94	7.33	
Mean value $\bar{x}$	7.31					
Standard deviation [s]	0.79					
$\bar{x}$ - ks (k=1.53)	6.1					
Stress Ratio (R_m/R_e)	1.15	1.15	1.15	1.15	1.18	(> 1.05)

Verification results of randomly tested TMT bar samples of other sizes (12 mm and 16 mm) under improved condition of the quenching process are given in Appendix 04.

After adjusting the inlet water pressure and water flow rate of the quenching box, the results obtained for Yield Strength and Elongation have shown a minimum variation from its mean value than before.

CHAPTER 05

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The existing latest theories over secondary steel bar manufacturing processes are reviewed and the problems/ issues highlighted by those theories are explored.

The mix-proportion of the main alloying chemicals, Si and Mn, and the CE values are found to influence the yield strength and elongation of TMT bars causing high variations of these properties among the bars of a set. Therefore, precise controlling of alloy addition during de-oxidation and de-sulphurisation treatment of liquid steel in the ladle is necessary to obtain a low variation in yield strength and elongation of TMT bars.

It is evident that the TMT bars manufactured under the improved combination of quenching parameters have shown a minimum variation from the mean value for Yield Strength and Elongation. Therefore, the quenching parameters shall be adjusted as per the experimental data for inlet water pressure and water flow rate according to the nominal diameters of the bars to be produced.

Based on the results of the experimental study, the following conclusions can be drawn to ensure consistent quality in TMT bars:

1. Ferro-silicon (Si) and ferro-silico-manganese (Mn) have to be added to the melt or liquid solution so that the mix- proportion of Si : Mn is 1 : 4 approximately.

2. Carbon Equivalent value in the melt or liquid solution has to be controlled to be in the range $0.37<CE< 0.4$ % by mass.

3. Improved parameter set-up of the water quenching process paves the way for consistent quality product.

5.2 Recommendations

Based on the results from the present work, recommendations are addressed to Steel bar manufacturers and other interested parties of reinforcing steel bars (TMT).

- Steel manufacturers those who do scraps recycling for TMT bars can use the findings on Carbon Equivalent value and mixed proportion of alloying chemicals for making improved quality products. This can be used as guidance for any scraps recycling industry as these are written based on practical experience on operational activities and can be applied in similar situations.

- It is recommended to optimize and set the parameters of the quenching process as per the experimental values, according to the sizes of the bars.

- Careful selection of scrap-steel is pave the way for producing high quality ingots. Standardization of the Billet manufacturing process is one of the best options for consistent quality. Life Cycle Analysis (LCA) is to be practiced at national level when importing steel accessories to the country, which is ultimately aimed for recycling.

- Those who are willing to study or practice practical aspects of reducing quality variation in tensile properties can refer this research work as a Case Study.

5.3 Suggestions for future study

Carbon Equivalent value does not capture many of the elements that form part of the composition of steel bars made from recycled steel.

A major concern is the case of Boron which is known to be introduced into induction furnace steel by their scrap origin and the boric acid binder often used in induction furnace ramming mass.

REFERENCES

[1] J.C. Herman, V. Leroy, *"Influence of Residual elements on steel processing and mechanical properties"*; C.R.M. rue Ernest Solvay 11, 4000 Liege, Belgium.

[2] IOSR Journal of Mechanical and Civil Engineering (IOSRJMCE), *"Improvement in yield strength of deformed steel bars by quenching using Taguchi method"* –, ISSN: 2278-1684 Volume 2, Issue 2 (Sep-Oct 2012), PP 01-11 *(http://www.iosrjournals.org)*

[3] ISO/TR 16078: 2013 (E/F) (First Edition), *Technical Report on the classification and designation systems for casting imperfections,* International Organization for Standardization, Geneva, Switzerland.

[4] SLS 375: 2009 (4th Revision), *Specifications for Ribbed Steel Bars for the reinforcement of concrete,* Sri Lanka Standards Institution.

[5] Malcolm S. Burton (Chapter 01), *Applied Metallurgy for Engineers,* School of Chemical and Metallurgical Engineering, Cornell University

[6] ISRI - Scrap Specifications Circular 2012 - *Guideline for Ferrous Scraps: FS-2012:, Guidelines for Nonferrous Scrap, Ferrous Scrap, Glass Cullet, Paper Stock, Plastic Scrap, Electronic Scrap, Tire Scrap,* Institute of Scrap Recycling Industries, Inc. 1615 L St.N.W., Suite 600, Washington, DC 20036-5664. (http://www.isri.org)

[7] Journal of Civil Engineering Research 2012- 2(1): 14-17, *"Performance Enhancement of TMT Rebar in accelerated Corrosion"*, DOI: 10.5923/j.jce.20 120201.03, Department of Civil Engineering, NITK, Surathkal.Srinivasnagar, 575025, India

[8] Edgar C. Bain, *"Functions of the alloying elements in steel"* Am. Soc. Metals, Metals Park, Ohio (1939) 312 pages.

[9] American Society for Metals, *"Properties and Selection: Iron, Steels, and High-performance Alloys"* Metals Handbook (1990) Vol.1 (10th edition), Am. Soc. Metals, Metals Park, Ohio.

[10] S.K. Duggal, "Building Materials" (Fourth Edition), Civil Engineering Department, Motilal Nehru Institute of Technology, Allahabad (U.P.), India

[11] BS 4449 : 2005, "*Hot rolled steel bars for the reinforcement of concrete"*, London: British Standards Institution.

[12] Thomas G. Digger, Samuel J. Rosenberg and Glenn W. Geil, *"Heat Treatment and Properties of Iron & Steel"*, National Bureau of Standards, Monograph. 88', Nov. 1, 1966, (Washinton D C – 20402)

[13] SLS 978 : 2004/ ISO 6892 : 1998 (E) *"Metallic Materials – Tensile Testing at Ambient Temperature"*, Sri Lanka Standards Institution.

[14] Smarajit Sarkar, *Presentation on "Advances in steelmaking and secondary steel making"*, Department of Metallurgical and Materials Engineering, NIT Rourkela

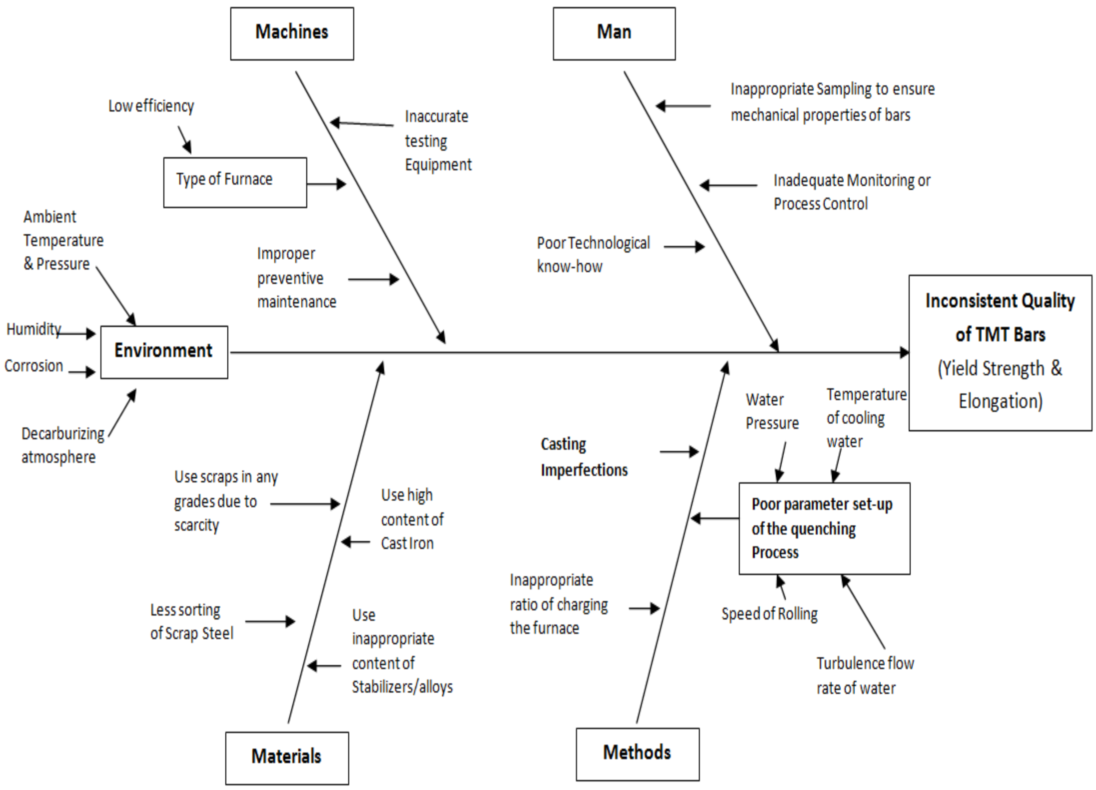
[15] MSE 300, Materials Laboratory Procedures, "*Fe-C liquid solution"*, Dept. of Materials Science and Engineering, University of Tennessee, USA

[16] Lauri Ho Jappa and Seppo Louhenkilpi, "*The role of ferroalloys in steelmaking"*, Department of Materials Science and Engineering, Aalto University School of Chemical Technology, Vuorirniehentie 2, PO Box 16200, FI-00076, Aalto, Finland.

[17] Mehran Maalekian "*The Effects of Alloying Elements on Steels"*, (published in October 2007), Christian Doppler Laboratory for Early Stages of Precipitation, The Graz University of Technology (TU Graz), Austria.

[18] Jacob Selzer "*Quenched and Tempered bar*", a publication of the Association for Iron & Steel Technology, August 2012 (AIST.org), http://www.ral.neu.edu.cn

Cause and Effect diagram



Improving the quenching parameters

Size of rebar: 10 mm   Bar speed: 4.76 m/s   Temperature of the cooling water: 30 – 40 ^{0} C

Water Pressure (kg/ mm^2)	Water Flow rate (m^3/ h)	Mass per metre run (kg)	Cross sectional area (mm^2)	Yield strength R_e (N/mm^2)	Tensile strength R_m (N/mm^2)	Stress ratio R_m/ R_e	Valve positions of the TMT box			
							1st set	2nd set	3rd set	4th set
10	90 – 110 m^3/ h	0.588	74.9	626.28	686.89	1.10	01 – 05 % opened	10 – 20 % opened	30 – 40 % opened	80 – 90 % opened
9.5		0.591	75.34	560.30	618.28	1.10				
9.5		0.609	77.63	513.03	631.42	1.23				
10		0.591	75.34	566.32	605.38	1.07				
10		0.592	75.47	605.09	746.28	1.23				
10		0.600	76.39	582.05	737.26	1.27				
10		0.608	77.39	551.18	608.19	1.10				
10		0.598	76.18	515.96	630.61	1.22				
9.5		0.590	75.18	533.24	671.49	1.26				
9.5		0.593	75.50	562.50	675.00	1.20				
9.5		0.594	75.63	545.52	564.33	1.03				
9.5		0.599	76.36	502.16	622.68	1.24				
9.5		0.601	76.52	511.05	602.31	1.18				
9.5		0.599	76.27	536.71	610.74	1.14				
9.5		0.613	78.14	508.04	639.75	1.26				
10		0.601	76.59	533.24	570.02	1.07				
10		0.601	76.57	622.66	659.29	1.06				
9.5		0.600	76.47	536.36	590.00	1.10				
10		0.593	75.52	622.75	765.10	1.23				
9.5		0.603	76.76	563.72	657.68	1.17				
9.5		0.594	75.68	502.30	538.18	1.07				
9.5		0.609	77.63	513.03	631.42	1.23				
10		0.591	75.34	566.32	605.38	1.07				
10		0.599	76.32	545.74	591.22	1.08				
10		0.601	76.59	564.96	659.12	1.17				

Dates: 2014-07-19 and 2014-07-20

Appendix 02

Size of rebar: 12 mm   Bar speed: 4.76 m/s   Temperature of the cooling water: 30 – 40 ^{0} C

Water Pressure (kg/ mm^2)	Water Flow rate (m^3/ h)	Mass per metre run (kg)	Cross sectional area (mm^2)	Yield strength R_e (N/mm^2)	Tensile strength R_m (N/mm^2)	Stress ratio R_m/ R_e	Valve positions of the TMT box			
							1st set	2nd set	3rd set	4th set
10	125 – 145 m^3/ h	0.883	112.43	516.42	609.11	1.18	05 – 10 % opened	10 – 20 % opened	40 – 50 % opened	80 – 90 % opened
10.5		0.856	109.10	558.41	618.78	1.11				
10.5		0.865	110.16	547.62	612.81	1.12				
10.5		0.869	110.69	556.87	609.91	1.10				
10.5		0.867	110.49	532.54	641.78	1.21				
10.5		0.867	110.40	524.19	615.92	1.18				
11		0.856	109.04	568.79	659.28	1.16				
11		0.871	110.99	525.12	617.02	1.18				
11		0.875	111.45	625.52	714.88	1.14				
11		0.879	111.95	594.92	672.51	1.13				
10		0.857	109.16	541.82	609.54	1.13				
10		0.872	111.15	543.32	646.81	1.19				
10		0.878	111.80	525.13	590.77	1.13				
10.5		0.871	111.00	541.41	616.95	1.14				
10.5		0.874	111.35	531.12	614.98	1.16				
10.5		0.863	109.95	535.96	640.54	1.20				
11		0.877	111.66	572.27	643.81	1.13				
11		0.885	112.73	574.04	616.05	1.07				
11		0.861	109.67	521.77	642.18	1.23				
11		0.863	109.97	582.53	693.49	1.19				

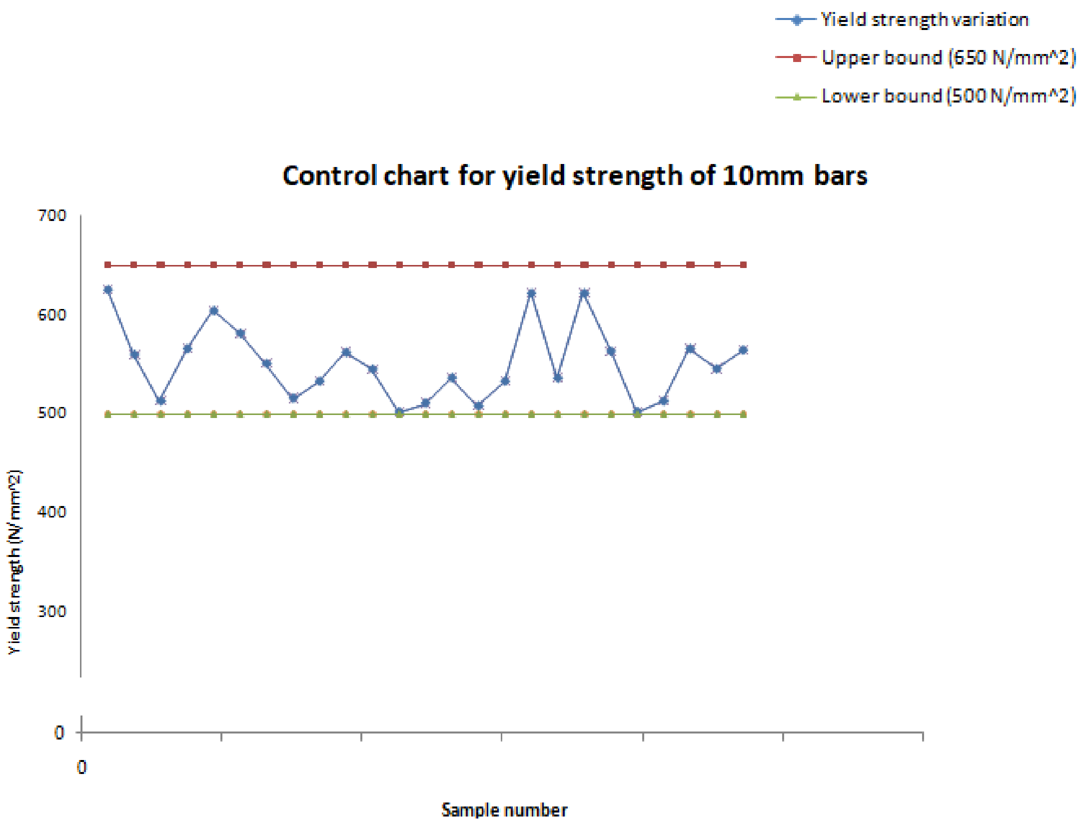
Dates: 2014-07-22 and 2014-07-23

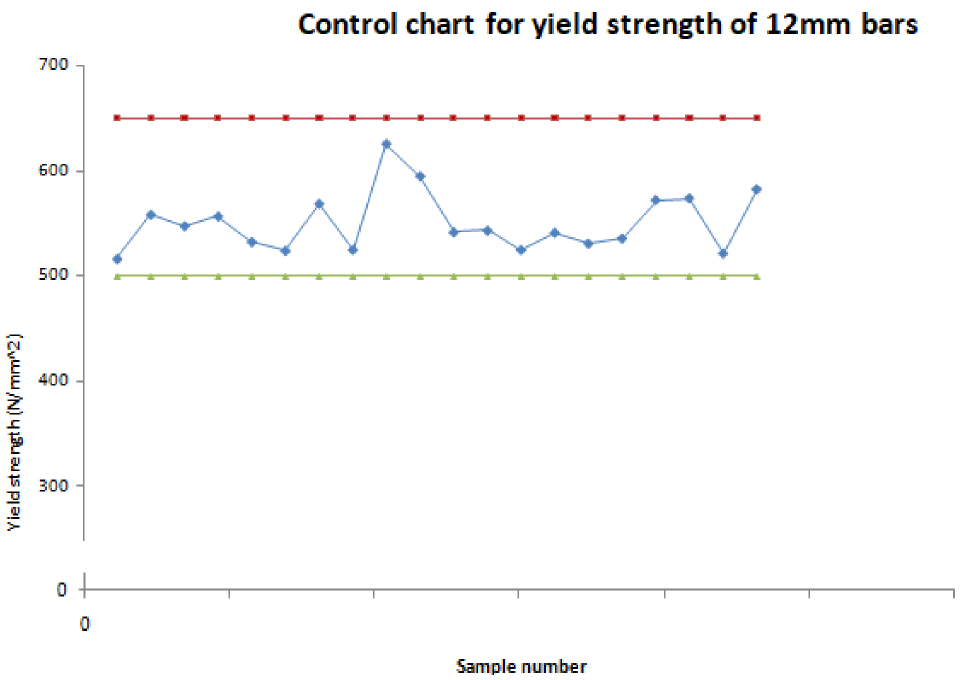
Size of rebar: 16 mm   Bar speed: 4.76 m/s   Temperature of the cooling water: 30 – 40 ^{0} C

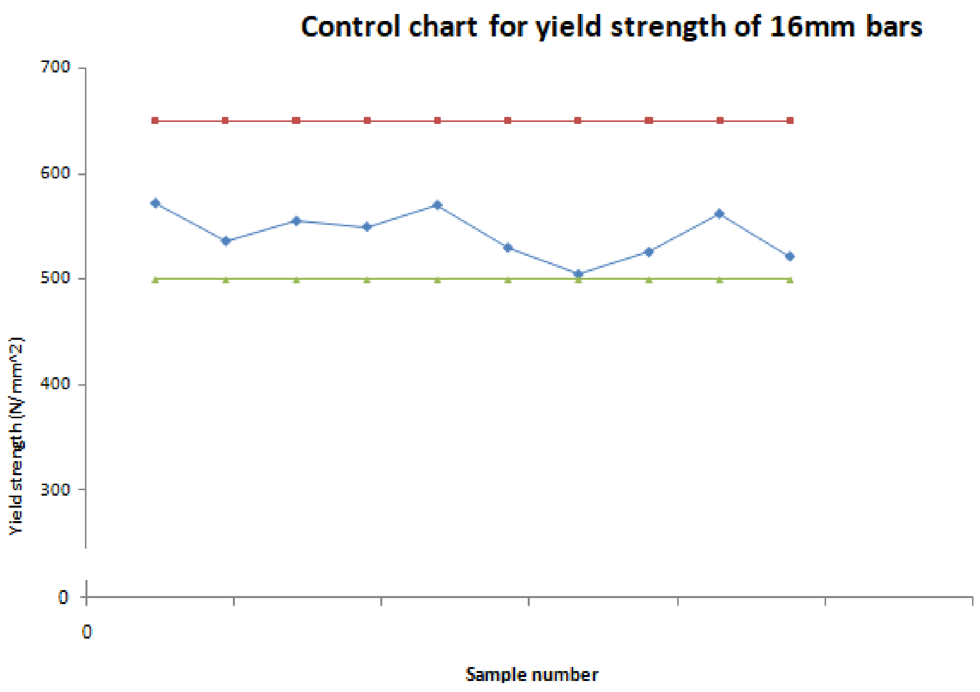
Water Pressure (kg/ mm^2)	Water Flow rate (m^3/ h)	Mass per metre run (kg)	Cross sectional area (mm^2)	Yield strength R_e (N/mm^2)	Tensile strength R_m (N/mm^2)	Stress ratio R_m/ R_e	Valve positions of the TMT box			
							1st set	2nd set	3rd set	4th set
11.5	230 - 250 m^3/ h	1.540	196.24	571.66	672.09	1.18	10 – 15 % opened	30 – 40 % opened	70 – 80 % opened	Full opened
11		1.522	193.83	536.10	571.84	1.07				
11		1.543	196.51	555.01	581.43	1.05				
11		1.525	194.27	549.58	593.20	1.08				
11		1.543	196.51	569.98	613.83	1.08				
11		1.578	201.04	529.88	578.05	1.09				
11		1.572	200.24	504.83	599.94	1.19				
11.5		1.522	193.83	525.82	609.64	1.16				
11.5		1.541	196.36	561.83	659.21	1.17				
11.5		1.555	198.10	521.74	640.99	1.23				

Date: 2014-07-18

Process control charts






Control chart for yield strength of 16mm bars
700
600
500
400
300
0
0
Yield strength (N/mm^2)
Sample number

Appendix 04

Conformity test results under improved control factor setting of the cooling system

Sample 01: TMT bars of size 10 mm

Parameter	Steel grade RB 500					SLS 375: 2009 Standard Specification (*size 10 mm*)
	Specimen number					
	01	02	03	04	05	
Mass per metre (kg/m)	0.614	0.602	0.600	0.611	0.600	0.588-0.644
Yield Strength (R_e) N/mm^2						650 > YS > 500
Individual	593.5	595.2	593.4	595.5	573.8	
Mean value $\bar{x}$	590.2					
Standard deviation [s]	9.2					
$\bar{x}$ - ks (k=1.53)	576					
Total elongation at maximum force (A_{gt}) %						(> 2.5)
Individual	6.24	7.74	8.34	6.94	7.33	
Mean value $\bar{x}$	7.31					
Standard deviation [s]	0.79					
$\bar{x}$ - ks (k=1.53)	6.1					
Stress Ratio (R_m/R_e)	1.15	1.15	1.15	1.15	1.18	(> 1.05)

Sample 02: TMT bars of size 12 mm

Parameter	Steel grade RB 500					SLS 375: 2009 Standard Specification (*size 12 mm*)
	Specimen number					
	01	02	03	04	05	
Mass per metre (kg/m)	0.873	0.857	0.859	0.857	0.863	0.848 - 0.928
Yield Strength (R_e) N/mm^2						650 > YS > 500
Individual	617.6	617.4	619.2	608.2	618.1	
Mean value $\bar{x}$	616.1					
Standard deviation [s]	4.4					
$\bar{x}$ - ks (k=1.53)	609					
Total elongation at maximum force (A_{gt}) %						(> 2.5)
Individual	7.55	11.55	9.35	8.05	7.55	
Mean value $\bar{x}$	8.81					
Standard deviation [s]	1.69					
$\bar{x}$ - ks (k=1.53)	6.2					
Stress Ratio (R_m/R_e)	1.16	1.14	1.16	1.15	1.15	(> 1.05)

Sample 03: TMT bars of size 16 mm

Parameter	Steel grade RB 500					SLS 375: 2009
	Specimen number					Standard Specification (*size 16 mm*)
	01	02	03	04	05	
Mass per metre (kg/m)	1.56	1.57	1.57	1.57	1.57	1.51 - 1.65
Yield Strength (R_e) N/mm^2						650 > YS > 500
Individual	579.5	595.1	597.0	597.0	595.7	
Mean value $\bar{x}$	592.8					
Standard deviation [s]	7.5					
$\bar{x}$ - ks (k=1.53)	581					
Total elongation at maximum force (A_{gt}) %						(> 2.5)
Individual	8.66	8.86	9.36	8.36	8.86	
Mean value $\bar{x}$	8.82					
Standard deviation [s]	0.36					
$\bar{x}$ - ks (k=1.53)	8.3					
Stress Ratio (R_m/R_e)	1.24	1.23	1.23	1.22	1.23	(> 1.05)

Spectrometer analysis data (cast analysis) used in the study

Charge No	C	Mn	Cr	Mo	V	Ni	Cu	CE	S	P	Si	Fe
1	0.177	0.725	0.057	0.021	0.0061	0.059	0.525	0.35	0.014	0.029	0.161	98.089
2	0.196	0.793	0.069	0.021	0.0036	0.051	0.615	0.39	0.021	0.023	0.213	97.904
3	0.169	0.817	0.061	0.026	0.0021	0.057	0.420	0.35	0.019	0.017	0.177	98.092
4	0.192	0.725	0.057	0.021	0.0060	0.059	0.600	0.37	0.014	0.029	0.210	97.999
5	0.190	0.919	0.063	0.023	0.0047	0.047	0.520	0.40	0.016	0.015	0.214	97.909
6	0.193	0.854	0.043	0.021	0.0023	0.056	0.610	0.39	0.029	0.021	0.219	98.065
7	0.186	0.845	0.047	0.018	0.0057	0.026	0.565	0.38	0.021	0.019	0.178	97.998
8	0.189	0.814	0.088	0.026	0.006	0.073	0.595	0.39	0.017	0.025	0.221	97.854
9	0.183	0.821	0.087	0.025	0.0059	0.064	0.475	0.38	0.028	0.029	0.209	97.968
10	0.200	0.844	0.058	0.024	0.0054	0.079	0.545	0.40	0.015	0.028	0.172	97.886
11	0.179	0.826	0.078	0.014	0.0077	0.059	0.455	0.37	0.017	0.021	0.196	98.021
12	0.196	0.910	0.014	0.016	0.0072	0.073	0.470	0.39	0.017	0.026	0.144	98.019
13	0.196	0.847	0.071	0.036	0.0071	0.088	0.390	0.39	0.028	0.028	0.205	98
14	0.198	0.915	0.076	0.025	0.0052	0.087	0.550	0.41	0.027	0.032	0.189	97.79
15	0.202	0.759	0.076	0.025	0.0055	0.090	0.455	0.39	0.029	0.032	0.207	97.994
16	0.185	0.751	0.057	0.029	0.053	0.072	0.355	0.37	0.014	0.028	0.197	98.141
17	0.201	0.798	0.061	0.023	0.0078	0.072	0.490	0.39	0.022	0.026	0.218	97.976
18	0.189	0.822	0.083	0.032	0.0077	0.086	0.595	0.40	0.03	0.023	0.196	97.825
19	0.201	0.872	0.071	0.026	0.0074	0.084	0.380	0.40	0.03	0.025	0.187	98.026

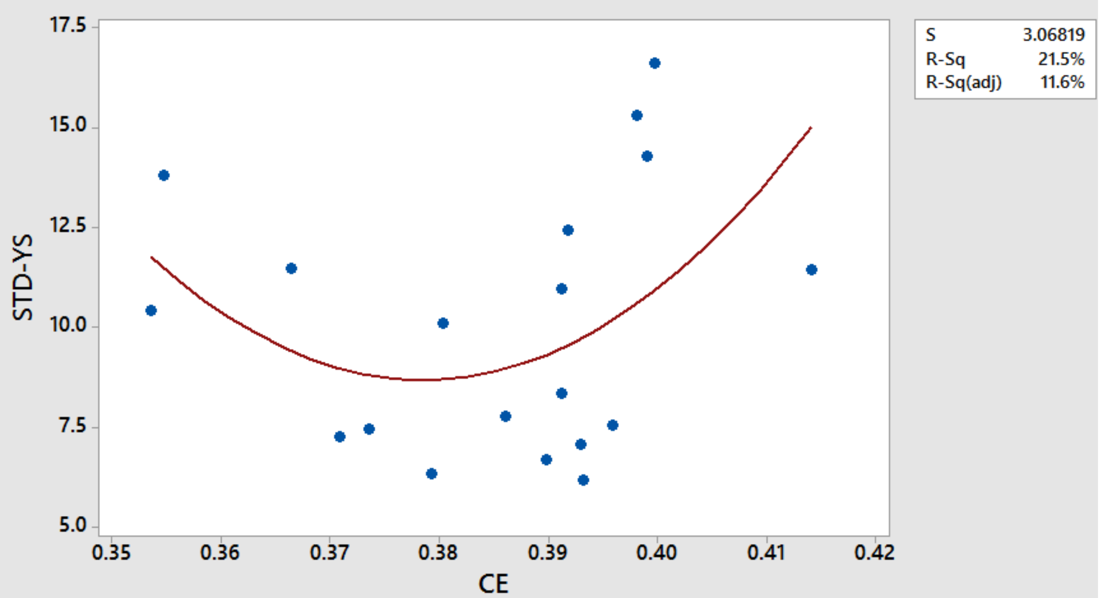
$$CE = \%C + \%Mn/6 + (\%Cr + \%Mo + \%V)/5 + (\%Ni + \%Cu)/15$$

Test data of the tensile properties (10 mm TMT bars)

Charge Number	Tensile Properties															
	Yield Strength (N/mm²)								Total Elongation at max force (%)							
	Individuals					Mean (X)	ST-DEV (S)	(X-ks) k=1.53	Individuals					Mean (X)	ST-DEV (S)	(X-ks) k=1.53
	1	2	3	4	5				1	2	3	4	5			
1	559.96	576.29	569.82	582.22	586.24	574.91	10.41	559.30	7.31	6.31	5.32	4.31	5.33	5.72	1.14	4.01
2	555.67	568.46	566.10	557.91	576.29	564.89	8.34	552.38	4.37	6.33	3.34	4.33	5.33	4.74	1.13	3.04
3	558.81	559.02	565.62	591.99	573.93	569.87	13.82	549.15	7.34	6.33	5.34	5.33	4.35	5.74	1.14	4.03
4	584.03	574.60	570.79	570.60	563.72	572.75	7.43	561.61	5.32	6.34	4.34	5.34	4.31	5.13	0.84	3.87
5	581.58	547.31	578.11	579.16	577.30	572.69	14.28	551.27	4.33	4.32	3.33	5.32	4.31	4.32	0.70	3.27
6	569.71	575.21	580.53	571.04	561.45	571.59	7.07	560.99	4.33	5.31	4.34	8.30	5.34	5.52	1.63	3.08
7	568.20	544.87	569.39	563.95	566.24	562.53	10.09	547.40	7.32	5.33	6.33	8.32	7.32	6.92	1.14	5.22
8	532.69	539.85	527.35	524.29	535.01	531.84	6.17	522.59	5.31	8.31	5.31	9.31	6.32	6.91	1.82	4.19
9	526.39	518.96	522.54	509.40	517.93	519.04	6.33	509.54	6.31	8.32	6.30	4.31	8.33	6.71	1.68	4.19
10	536.73	566.19	529.24	540.44	563.51	547.22	16.62	522.30	6.31	6.32	6.31	6.31	5.33	6.12	0.44	5.46
11	547.14	540.08	551.24	540.60	557.21	547.25	7.26	536.37	7.31	6.31	5.32	5.31	4.31	5.71	1.14	4.00
12	585.31	582.50	581.11	561.13	565.67	575.14	10.95	558.73	6.32	5.33	7.33	8.31	6.31	6.72	1.14	5.02
13	569.51	579.01	565.40	564.87	544.98	564.75	12.42	546.12	6.32	4.31	4.31	6.32	8.31	5.91	1.67	3.40
14	567.12	544.80	548.95	559.52	571.47	558.37	11.43	541.23	5.32	6.33	4.32	4.32	6.31	5.32	1.00	3.82
15	551.62	533.99	541.04	535.27	532.73	538.93	7.77	527.27	6.32	5.30	8.30	8.31	9.29	7.50	1.64	5.05
16	527.41	553.45	537.74	553.35	550.00	544.39	11.47	527.18	7.28	6.29	5.28	4.31	5.30	5.69	1.13	4.00
17	537.41	524.58	522.53	520.24	527.23	526.40	6.67	516.39	6.28	6.28	5.28	6.27	5.28	5.88	0.55	5.06
18	573.34	570.80	576.72	584.36	563.90	573.82	7.54	562.52	6.32	5.32	8.32	8.31	9.31	7.52	1.64	5.06
19	527.41	553.45	537.74	540.65	567.07	545.26	15.32	522.28	7.3	6.31	5.3	5.31	4.31	5.71	1.14	4.00
	500 < Yield Strength < 650								2.5 <							

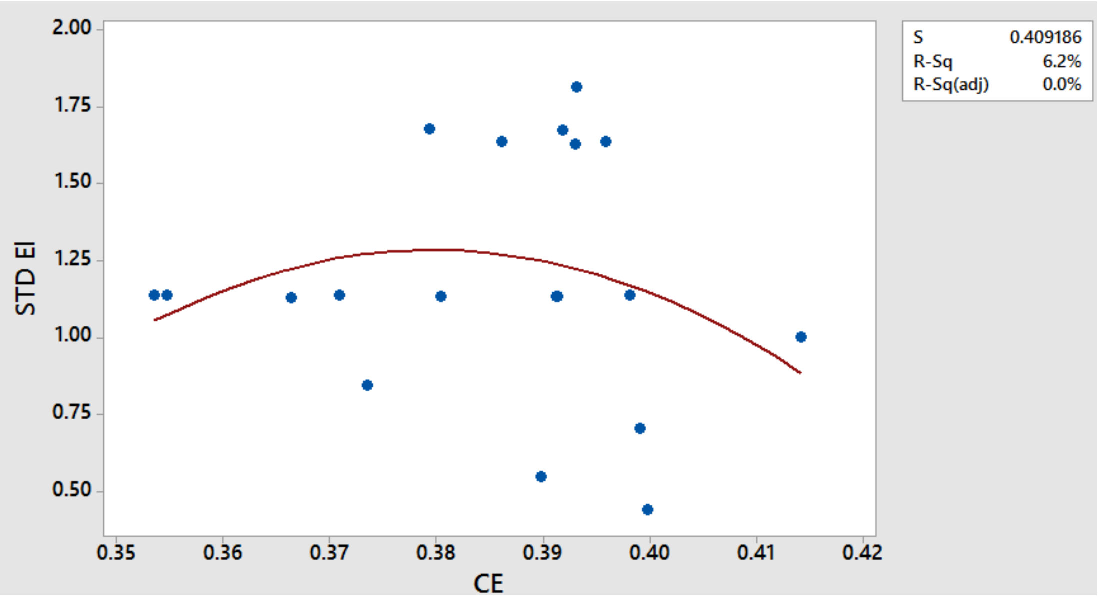
Plots created in second order polynomials (quadratic form)

01. Fitted line plot of CE vs. STD-YS in quadratic form



For the interpretation of data in plot-01, the S is 3.06819 units of STD-YS. Moreover, 21.5% of the variation in STD-YS is explained by CE.

02. Fitted line plot of CE vs. STD-El in quadratic form



For the interpretation of data in plot-02, the S is 0.409186 units of STD-El. Additionally, 6.2 % of the variation in STD-El is explained by CE.