

Development and characterization of Fe500S TMT rebars

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New varieties of high-strength rebar Fe500S with superior seismic resistance properties have been developed to meet future needs of construction in seismic prone areas. Billets have been produced by standard steel making process route (BOF-LF-CC) with the exception of chemical designing, which has been uniquely improvised so as to reduce the alloying cost. Reheated billets have been rolled into final TMT rebars by varying the operation parameters such as velocity and quenching rate. Chemical properties, surface morphology, and mechanical properties of the thus-produced TMT rebars have been studied by OES (spark analysis), optical microscopy, tensile, and hardness tests. Cost analysis has shown attenuation in the alloying cost by a margin of Rs. 855 per ton. Mechanical properties as evaluated from tensile tests have also yielded a positive outcome in the form of better tensile strength (UTS/YS ratio) and hardness. All the results have been compared with the Indian Standard IS 1786:2008.

Keywords: Fe500S, TMT rebars, Cost optimization, OES, Tensile, Hardness

1 Introduction

Geographical stats of India display that nearly 59% of the land area are prone to earthquakes. The frequent high intensity earthquakes in India are caused by the fact the Indian plate is moving towards Asia at a formidable rate of 47mm per year¹. Estimations from the reports of The United Nations and World bank indicate that nearly 200 Million population of India will face the risk of severe earthquake and storm in the next 30 years²⁻³. As these natural calamities in the form of earthquake, cyclone and blizzards can't be avoided, strong and robust habitats and structures are need of the hour to minimize casualties and economic loss. As we see from the geographical statistics and trend that India and its surrounding lands will be hit by frequent earthquakes, there is a serious demand to the development of earthquake resistant structurals. TMT rebars are the backbone of any structure and as such, recent studies focussed more on fatigue types (low cycle, high cycle), strain behaviour during high strain rate, high temperature behaviour of TMTs in order to bring out the best quality TMT bars. In order to acquire high quality TMT rebars, recent studies investigated like the low-cycle and high-cycle

fatigue^{3,4,11,12}, stress corrosion cracking¹³⁻¹⁴, high strain-rate¹⁵ and high temperature behaviour of TMT rebars¹⁶

The swift growing construction industry has favoured the use of hot rolled rebars as we see the positive slope in production and consumption of such rebars over the last few years. Factors such as high strength, UTS/YS ratio, superior weldability, corrosion resistance, ductility and durability make these TMTs ideal as reinforcement entity in concretes³⁻⁸. UTS/YS ratio of TMT is the main reason for its durability (fatigue strength) to higher seismic loads. Highlighting all these aforementioned conditions, Burnpur Steel Plant endeavoured production of seismic resistant Grade 500S (Fe500S) TMT rebars as per Indian standards IS: 1786:2008. Civil structures undergo a lot of tensile forces and these rebars take care of them. In addition to efforts of enhancing the yield strength, considerable focus is given to provide better safety in the event of an earthquake in the seismic prone zone. BIS specification IS 1786:2008 for high strength steel bars was suitably revised in 2012 to let in two grade of Fe415S and Fe500S with enhanced UTS/YS ratio of 1.25 minimum, and higher elongation in TMT rebars ensure greater energy absorption capacity in the civil structures in the event of an earthquake and minimum the risk of collapse and loss of human life.⁶⁻¹⁰

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In this research trial of TMT rebars of diameters 8mm were produced without vanadium in accordance with regulations of IS 1786:2008 Fe500S grade with additional corrosion resistance property. As we know that properties of TMT rebar depend on:

- Alloying Element
- Rolling Parameter. (Process Parameter)

2 Materials and Methods

A random Fe500S rebar samples with a cross section of 8 mm (coil) which was developed through different vanadium and Manganese content to optimised total alloying cost was examined. Chemical analysis (Table 1) with the help of Optical Emission Spectrometer (OES) confirm that it comes under seismic resistant rebars. Specimens were prepared by polishing and etching freshly prepared 2% Nital (2ml HNO₃ and 98ml ethanol or methanol) solution for the microstructure. Etching was done by dipping the polished surface gently in the etching reagent for 15 to 20 second and after hot air is used to dry the sample. The machine which is used for tensile testing is Universal Testing Machine (52/191, manufactured by Alfred J. Amsler & Co. Switzerland Indian importers Voltas Limited). For testing we referred, IS 1786:2008 (Indian Standards) specification in which gauge lengths for most round specimens are required to be 5.65A1/2(5D) for Fe500S; where D means diameter of the specimens. Vickers hardness test was carried out at two different sections (core & rim) by using Vickers Pyramid Hardness testing machine (Serial no-HTM7510).

2.1 Alloying elements

Chemical designing had been done by specifically focusing on manganese and vanadium content. It has been found that, although vanadium content yields better mechanical properties, but the cost associated with it gets very high and hence not pragmatics as per prices of Ferro alloys as per January 2018 were taken from steelmint.com. To

Table 1 — Chemical composition (in %) as per Indian Standard.

Steel ID	C	Mn	S	P	CE
Heat no 1717					
As per IS 1786:2008 Content (maximum in %)	0.25	1.47	0.04	0.04	0.53
Sample 1	0.24	1.45	0.03	0.026	0.49
Sample 2	0.22	1.45	0.029	0.021	0.47
Sample 3	0.24	1.45	0.03	0.026	0.49

resolve this issue, various trials were carried out at IISCO Steel Plant, Burnpur by varying the content of Vanadium and Manganese. During first trial the UTS/YS ≥ 1.25 was observed with addition of Manganese (Mn) 1725kg and Vanadium (V) 36kg with alloying cost INR 2432 per/ton which was not very favourable condition keeping in view prices of Ferro alloys as per January 2018, taken from steelmint.com as shown in Table 2.

During second trial, the addition pattern was changed to Manganese (Mn) 2719kg and Vanadium (V) 0 kg. Good mechanical property observed (UTS/YS ≥ 1.25) and total alloying cost was around INR 1799 per ton. The difference in cost with Vanadium and without Vanadium has been compared in Table 3.

During third trial, Manganese 1911kg and with zero vanadium content, the rolling parameters were changed, water flow rate from 80 to 50% valve opening and mill speed 40 to 50 m/s considerably to achieve desired property.

By compensating the decrease in vanadium (0%) content & increase in Manganese content during the second trial and then after cost analysis, it has been found that costing is attenuated as shown in Table 4. And graph below (Fig. 1). During third trial with lower Mn content without V and optimise rolling parameter, cost cutting was considerable and hence this chemical design is adopted for final alloy preparation.

Table 2 — Cost of alloying element.

Ferro Alloy	Total Additions(Kg)	Cost of Ferro alloy(Rs/Kg)	Total (Rs)
SiMn	1725	71.75	123768.8
HCFeMn	1402	76	106552
FeSi	491	107.5	52782.5
Pet Coke	178	27	4806
FeV	36	1800	64800
	Total alloying cost per heat		352709.3
	Total alloying cost per ton		2432

Table 3 — Cost of alloying without Vanadium.

Ferro Alloy	Total Additions (Kg)	Cost of Ferro alloy (Rs/Kg)	Total (Rs)
SiMn	2719	71.75	195088.3
HCFeMn	500	76	38000
FeSi	223	107.5	23972.5
Pet Coke	142	27	3834
FeV	0	1800	0
	Total alloying cost per heat		260894.8
	Total alloying cost per ton		1799
	Difference in cost with Vanadium		633

3 Results and Discussion

3.1 Characterization

3.1.1 Optical emission spectrometer (Spark analysis)

The chemical composition analysis of given sample which is obtained from RDCIS, Ranchi follow as per Indian standard IS 1786:2008 Fe500S, as shown in Table 1. With the help of Optical Emission Spectrometer (Spark Analysis), we can confirm that our sample come under seismic resistance rebars.

Table 4 — Cost of alloying without Vanadium.

Ferro Alloy	Total Additions (Kg)	Cost of Ferro alloy(Rs/Kg)	Total (Rs)
SiMn	1911	71.75	137114.3
HCFeMn	883	76	67108
FeSi	173	107.5	18597.5
Pet Coke	221	27	5967
FeV	0	1800	0
Total alloying cost per heat			228786.8
Total alloying cost per ton			1578
Difference in cost with Vanadium			855

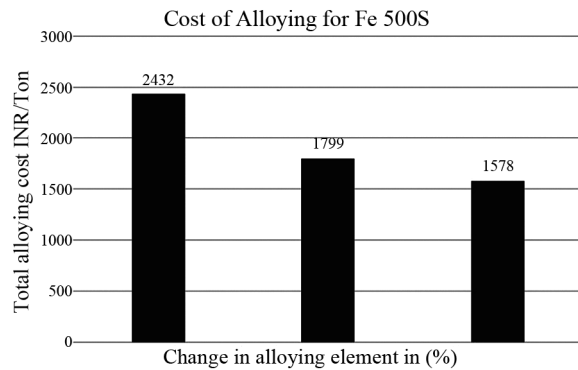


Fig. 1 — Alloying cost with variation in Mn & V content.

3.1.2 Microstructure

The observed microstructure of TMT rebars under an optical microscope of several zones like core, intermediate and case of TMT rebars under different magnification is presented in Fig. 2 & 3. Microstructural examination of the samples from all the experiment carried out by polishing the transverse section of rebar and treating them with freshly prepared 2% Nital solution. This was done to determine the phase present in the rim and the core, tempered martensite rim thickness, and ferrite grain size.

A typical microstructure of Fe500S rebar clearly revealed the circular tempered martensite rim on the surface (Fig. 2). Circular rim form due to the intense but short duration water quenching of the rebar surface when it travels through the different water cooling zones. The martensite thickness or the volume fraction of martensite on the rim depends upon the intensity of water cooling measured by water pressure and flow rate which is controlled through water valve opening in different cooling zones. The volume fraction of tempered martensite was determined for a number of such Rebar produced under different cooling conditions. Figure 3 depicts the typical microstructures observed in core areas, and as can be seen, they are totally different. Observational evidences of fully developed black grain (pearlite) and white ferrite grains at the core validate proper heat treatment of the thus produced TMT rebars. Ferrite and pearlite grain size of core and average rim

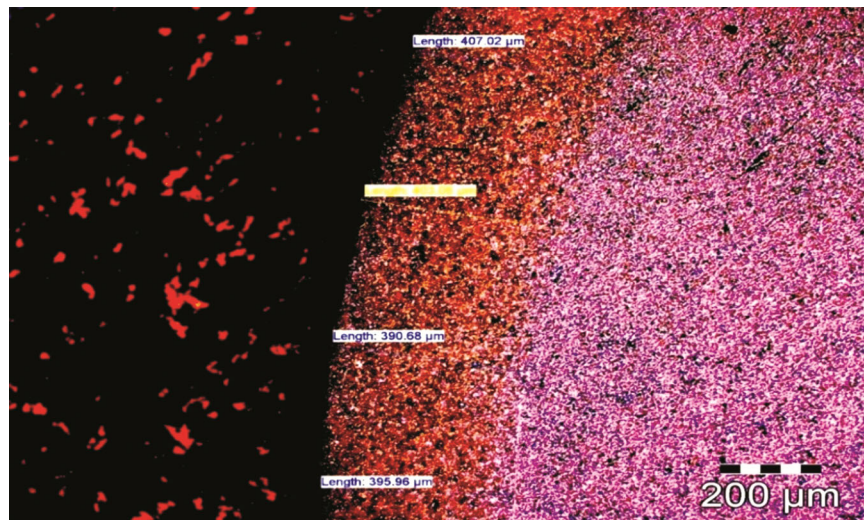


Fig. 2 — Microstructure of intermediate zone and rim thickness of Fe500S TMT rebars.

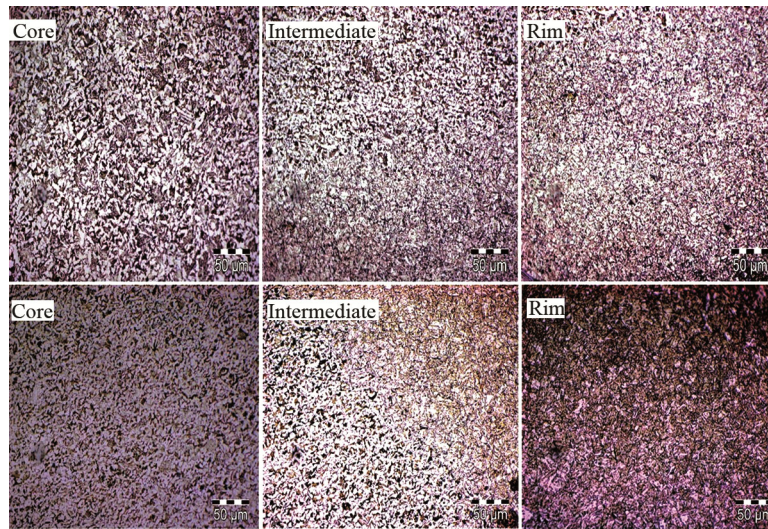


Fig. 3 — Microstructure of core, intermediate zone and rim with the help of optical microscopy.

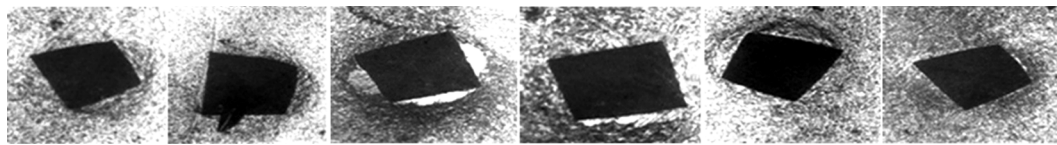


Fig. 4 — Indentation image of sample after Vickers hardness test.

Table 5 — Grain size and Rim thickness of tempered martensite.

Sample	Avg. Grain Size (µm)	Avg. Rim Thickness (mm)
1	10.1	0.447
2	9.3	0.289
3	10.5	0.293

Table 6 — Hardness value of Fe500s TMT rebars.

Sample	Surface area	d ₁	d ₂	d _{avg}	HV
1	CASE	218	226	222	376
	CORE	269	290	280	237
2	CASE	228	244	236	333
	CORE	287	297	292	217
3	CASE	230	238	234	339
	CORE	279	297	288	224

thickness of tempered martensite which is obtain from Image software are given in the Table 5.

Average grain size which is obtain from optical microscopy of sample 1 & 3 are within the range according to Vinodkumar,¹⁸ but average rim thickness are not according to as per IS 1786:2008 because sample which is used for optical microscopy prepared after tensile testing of rebars.

3.1.3 Hardness testing

Vickers hardness test of TMT rebar was carried out at two different section (core & rim) by using Vickers Pyramid Hardness testing machine (Serial no- HTM7510) as shown in the Fig. 4 below and the

results of Vickers hardness testing (load 10 kg) are shown in Table 6.

The hardness of core of TMT rebars are lesser than case hardness. This can be explained by the fact that the core is composed of fine grained ferrite and pearlite which makes it ductile whereas the outer is composed of brittle tempered martensitic structure. From Table 6, it is evident that sample one scores highest in terms of case and core hardness than sample 2 & sample 3. A crucial reason behind this is the variation in reheat temperature, rolling speed and quenching rate. These all parameter had an effect on equalization temperature. In optical microscopy test, it also has been observed that rim thickness of sample no. 1 is higher than other sample. So sample no. 1 should have high hardness value, which has been observed during hardness as shown in Fig. 5.

3.1.4 Tensile testing

The tensile properties were obtained by using universal testing machine are tabulated in Table 7 below (52/191, manufactured by Alfred J. Amsler & Co. Switzerland Indian importers Voltas Limited).

The yield strength of sample 2, 3 and ultimate tensile strength of sample 2, which is obtained from universal testing machine at NIFFT, Ranchi do not follow as per

Indian Standard IS 1786:2008 Fe500S Rebars, but all other parameter is good as per standard.

The main reason behind it is that the sample which is obtain from wire rod mill was not straight (coil) and was made straight by clamping the sample with the help of two jaw of UTM machine, left it for three hours after applying tensile load.

Data from Table 7 suggest that UTS and YTS of sample 3 are far more than sample 1 & 2, which is again explicit from their hardness values. While comparing between the sample 1 & sample 2, it is seen that elongation percentage of sample 1 is higher; i.e. sample 1 is more ductile. Data obtained from RDCIS Ranchi after tensile testing are listed in Table 8, which also support previous tensile testing result. All these results validate the good combination of strength and ductility in the TMT rebars produced. A comparative data (YS, UTS) obtain from universal testing machine of sample 1, 2 and 3 are listed in fig. 6.

Figure 7 above illustrates the fracture mode of all the three as-received Fe500STMT rebars with exterior surface ribs. It is seen that all the three fractures are of

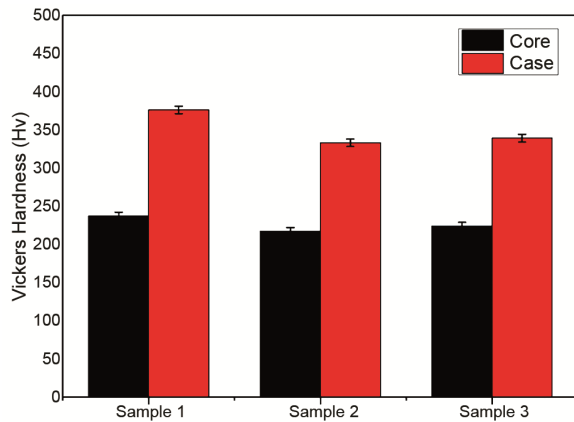


Fig. 5 — Vickers hardness graph.

cup and cone type which is typical for any ductile material. Ductile type of fracture for steel bars as concrete reinforcing material is common. Because concretes are composed of very brittle particles, compressive strength for concrete goes much higher whereas the bending and tensile strength are very low. As such with the addition of high strength ductile cored TMT rebars, the concretes get protection from cracking and collapse under high tensile load. Hence, the risks of sudden failure and eventual collapse of



Fig. 6 — Mechanical Properties of Rebar.

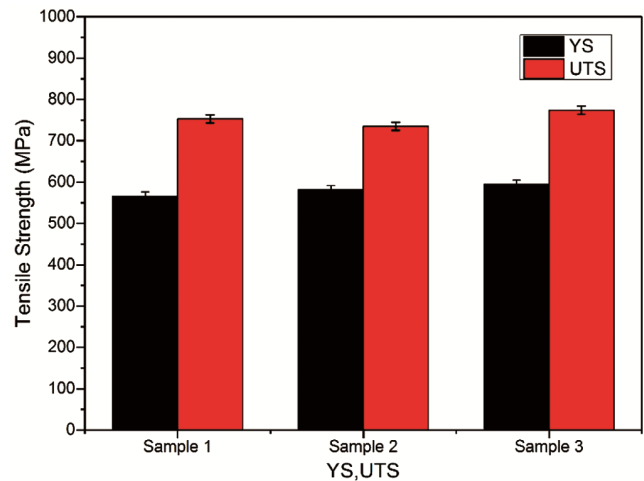


Fig. 7 — Image showing ductile fracture mode of TMT rebars sample 1, 2 & 3.

Table 7 — Tensile testing result.

Sample	Nominal Dia. (mm)	Area (mm ²)	Gauge length (mm)	YS (MPa)	UTS (MPa)	UTS/YS Ratio	% El
Sample 1	7.8	47.78	40	508.66	695	1.37	25.62
Sample 2	8	50.26	40	465	610	1.31	24.13
Sample 3	8	50.26	40	477	653	1.37	Broken from outside GL

Table 8 — Tensile properties of Fe500s TMT rebars used.

Sample	Nominal Dia. (mm)	Area (mm ²)	Gauge length (mm)	YS (MPa)	UTS (MPa)	UTS/YS Ratio	% El
Sample 1	8	50.26	40	566	753	1.33	25
Sample 2	8	50.26	40	582	735	1.26	25
Sample 3	8	50.26	40	595	774	1.30	25

concretes composed of brittle aggregates; improperly casted or curated, gets eradicated by the addition of TMT bars as reinforcement. As a result the safety of the concrete structures gets increased. The ductile TMTs should have lesser residual stress to ensure lower corrosion rate.

3.1.5 Rolling parameter

Rebars are mandatory material during any construction work and that is why temperature at which rebars should be manufactured must be controlled to ensure superior product. Temperature control gives an upper hand in the handling of strain rate, recrystallization and flow stress during the rolling process. Cooling condition also needs to be optimized to assure the correct outer hardness of the rebar during quenching (equalization temperature). A perfect tempering temperature for the composition brings out amicable ratio of quantity (volume) and hardness variation starting from hard exterior part to the inner pearlite-ferrite core. The parameters for cooling conditions also include rolling temperature, quenching temperature, and pressure of spray and velocity of billet movement.

Equalization temperature is the extreme temperature formed at the rebar outer surface after quenching played very important role in the formation of tempered martensite. If Equalization temperature is less, more tempered martensite formation took place and TMT rebars became brittle and fail during tension. It can be easily control by changing rolling speed and quenching rate and during the trial good mechanical properties were achieved as per IS 1786:208 at the bar speed of 50-60 m/s and water box valve opening at 30-40%.

4 Conclusion

- Chemical designing had been done by specifically focusing on manganese and vanadium content and by changing rolling parameter, quenching rate and cost of production reduced by 855Rs/ton (cost of alloying).
- Properties of samples from trial rolling of 8 mm TMT coils of Fe 500S billets without Vanadium was found confirming to the relevant IS 1786:2008.

- During trial the properties were achieved at the bar speed of 50- 60 m/s and water box valve opening at 30-40%, earlier was 80% valve opening.
- Fe500S TMT rebars have the same microstructure, which consists of an inner core of ferrite and pearlite and an outer martensitic rim with an intermediary narrow transition zone.

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