'TM-Ring Test' - A quality control test for TMT (or QST) steel reinforcing bars used in reinforced concrete systems

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Sooraj A. O. Nair and Radhakrishna G. Pillai

Abstract

The Thermo-Mechanically Treated (TMT) steel is commonly referred to as Quenched and Self-Tempered (QST) steel. The cross-section of good TMT/QST steel reinforcing bars (rebars) is required to have a ductile core of 'ferrite-pearlite' (FP) and a continuous, uniformly thick, and hard 'tempered martensite' (TM) microstructure as the peripheral ring. However, recent studies on TMT/QST steels in the Indian market show the presence of discontinuous, eccentric, and non-uniform TM-phases at the periphery, which can be attributed to the improper quenching. This could result in localized corrosion and variations in the mechanical properties. Although IS 1786: 2008 mentions the etching of steel to identify the microstructural phases, it is an incomplete (lacks necessary test protocols; leads to unreliable results) and non-mandatory provision given in the annexure. In this scenario, a standardized test is essential to assess the quality of TMT/QST steel rebars. This paper fine-tunes and proposes the "TM-ring test" to characterize the cross-sectional phase distribution in TMT/QST rebars. In particular, the details on specimen extraction, preparation, testing and analysis, which are crucial to obtain reproducible and reliable results, and a 2-level acceptance criteria for TMT/QST rebars are provided for further incorporation in the standard specifications.

1 Introduction

The steel market has grown tremendously over the decades and has been meeting the demand for better mechanical and corrosion performance. The need for both high strength and ductility led to the evolution of mild steel to Cold Twist Deformed (CTD) steel rebars, and then to Thermo Mechanically Treated (TMT) steel by the 1990s (Viswanatha 2004). TMT steel rebars are used in other countries as well and known by the name of Quenched and Self-Tempered (QST) steel. In the strict technical sense, TMT could refer to a range of steel products that undergo a thermal and mechanical processing in the manufacturing line like QST, Ultra Fine Grained (UFG), Dual Phase (DP) and Transformation Induced Plasticity (TIP) steels (Islam 2010). The term TMT came from the common usage during its earlier days in the Indian steel market and is being continued thereafter. In this paper, the term TMT/QST is used to refer the TMT steel rebar.

The schematic of QST process is shown in Figure 1 (Varghese 2005). Better mechanical performance at reduced production cost can be achieved through quenching and self-tempering (QST) over cold-hardening or micro-alloying (Augusti 1995). This makes TMT/QST steel rebars being widely used in India today. The cross-section of a typical TMT/QST steel rebar cross-section is given in Figure 2. The QST process is supposed to form a composite cross-section of a hard peripheral ring of tempered martensite (TM) and a soft ductile core of ferrite-pearlite (FP) microstructures in a TMT/QST steel rebar. The hard outer ring and soft inner core are predominantly responsible for the high strength and ductility, respectively, of TMT/QST steel rebar.

1.1 Manufacturing Technology for TMT/QST rebars

The quenching and self-tempering processes are employed in the manufacturing line with the help of various cooling technologies. These patented technologies like Tempcore™, Thermex™, Stelmor™, Thermoquench®, Evcon Turbo™ etc. essentially have a cooling system, which uses air, water, or both at specified temperatures and flow rates. Noville (2015) discusses about the effect of the quenching parameters (line speed, water temperature, quenching time, etc.) on the microstructure and mechanical properties TMT/QST

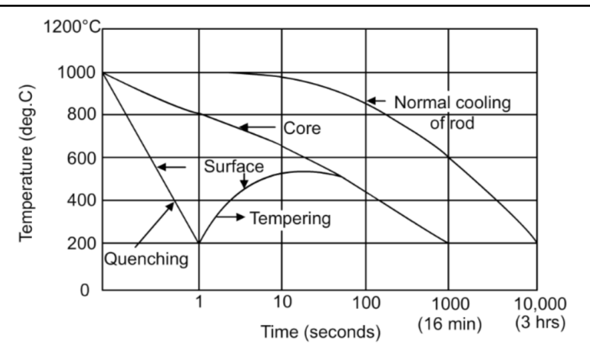


Fig. 1 Schematic of a QST process (Varghese 2005)

Keywords: Concrete, Steel Rebar, TMT, QST, Martensite, Ferrite, Pearlite, Quenching, Tempering, Etching, Quality Control

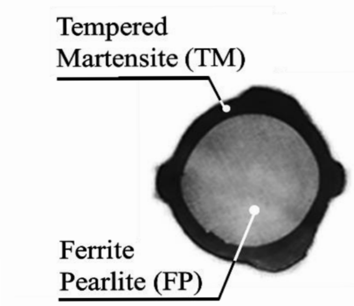


Fig. 2 Typical cross-section of a good quality TMT/QST rebar

steel rebars using Tempcore™ technology, and Gamble (2003) discusses about Thermex™ processed reinforcing steels. Other than these, documentation on the differences in the quenching and self-tempering processes and outputs, across various quenching technologies could not be found by the authors.

The microstructure of hot billets rolled to a specific diameter, at the temperature of rolling, are in austenitic phase. This passes through a cooling system that rapidly reduces the surface temperature (i.e., quenching) of the rolled product from about 1000 to 200 °C (i.e., a reduction of about 800 °C) within about a second. The resultant hard martensite at periphery is then self-tempered by the radial heat transfer from the hot core to the surface. Then in the cooling bed, the austenitic core transforms to ferrite-pearlite (FP) by slow cooling in air. Although a qualitative understanding of the process is clear and similar for all the available quenching technologies, details are not mentioned in the international specifications for the manufacturing of steel rebars such as IS 1786 (2006), ASTM A706/706M (2014), BS 4449 (2005), DIN 488-1 (2009), JIS G3112 (2004) etc.

1.2 Indian standards for the manufacturing of TMT/QST steel rebars

IS 1786:2008 (High Strength Deformed Steel Bars and Wires for Concrete Reinforcement – Specifications) provides guidance on the manufacturing and quality control (QC) of TMT/QST steel rebars. However, it does not mandate the requirement of attaining the desired cross-sectional phase distribution (herein, termed as CSPD) with TM-ring and FP-core, as shown in Figure 2. Moreover, Annex A of IS 1786:2008 is titled 'Information on controlled cooling process' and provides minimal details for assessing the CSPD of steel rebars. A snapshot of Annex A is provided in Figure 3. Further, the last portion of Annex A states, "...this test is not to be regarded as a criterion for rejection...". The reason for this avoidance of stringent measures is unknown to the authors.

Also, the specifications on the critical manufacturing parameters such as line speed, water temperature, quenching time, etc. for the heat treatment of rebars with different diameters are not mentioned in IS 1786:2008. It should be noted that these parameters have significant influence on the formation of appropriate CSPD and are dependent on the technology adopted in the manufacturing line such as Tempcore™, Thermex™, etc. and could not be generalized. Noville (2015) shows the change in CSPD with respect to the quenching parameters in a Tempcore™ cooling system. Further discussions on the control over these parameters are beyond the scope of this paper.

1.3 Effect of discontinuities on the properties of TMT/QST steel rebars

A good quality TMT/QST rebar must have a continuous, concentric and uniform TM-ring, as shown in Figure 2. However, many poor quality rebars (including TMT/QST) in terms of geometry, rolling and mechanical properties- do exist in the Indian market (Viswanatha et al. 2004). Although some key industry personnel are aware of such issues, very few articles (Ambuja 2005; Nair et al. 2015) mention about the inadequate quenching and the resulting discontinuous, eccentric, and non-uniform TM-rings. In such poor quality rebars, the peripheral TM-ring is discontinuous with FP exposed at the rebar surface or circumference. Figure 4 shows three typical CSPDs of good quality (Case A) and poor quality (Cases B, C, and D) TMT/QST steel rebars obtained from the laboratory experiments in this study. Cases B, C, and D could result in preferential and localized corrosion (Nair et al. 2016). Also, based on electrochemical experiments conducted on coupon specimens extracted from representative TMT/QST steel rebar collected from the market, Nair et al. (2016) reported that FP could have lower chloride threshold than TM. Hence, TMT/QST steel rebars with discontinuous TM phase at the periphery could experience an earlier initiation of corrosion than a good quality rebar. Also, the discontinuities could affect the mechanical properties of the TMT/QST rebars (Mamun Al Rashed and Shorowordi 2015).

The strength and ductility of a TMT/QST bar is predominantly attributed to quantity of TM and FP phases in the CSPD, respectively. The typical area constituted by ferrite pearlite in TMT/QST steel rebars is 65-75% (Markan 2005). However, the presence of discontinuities could lead to variation in the yield strengths from the specified strength-grade due to the higher area of FP. However, IS 13920 (1993): 'Ductile Detailing of reinforced concrete structures subjected to seismic forces – code of practice' and IS 1786:2008 do not specify any upper limits for yield and tensile

IS 1786 : 2008

ANNEX A

(*Foreword*)

INFORMATION ON CONTROLLED COOLING PROCESS

A-1 The processing of reinforcing steel is usually through one or combination of processes which may include hot rolling after microalloying, hot rolling followed by controlled cooling (TMT process) and hot rolling followed by cold work.

Heat treatment is a thermal process undergone by the steel in the solid state. The most common practice is finishing online heat treatment while rolling, commonly known as thermomechanical treatment (TMT) process. After leaving the last stand of the rolling mill, the bars are quenched (rapidly cooled) in water from a final rolling temperature of about 950°C. The quenching is partial, only until a surface layer has been transformed from austenite (a steel phase stable only at very high temperatures) to martensite (stable at temperatures below 350°C). This controlled quenching is achieved in one or more online water cooling devices through which the steel passes at a very high speed before reaching the cooling bed.

Because the quenching is only partial, a part of the original heat remains in the core of the steel and, on the cooling bed, this heat migrates towards the surface. This results in an automatic self-tempering process where the surface layer of martensite is tempered; this 'tempering temperature' (or equalization temperature) refers to the maximum temperature attained by the bar surface after quenching. Tempering enables a partial diffusion of carbon out of the extremely brittle but strong martensite, thus relieving the inherent stresses locked in during the sudden quenching of the red-hot steel in cold water. The resulting tempered-martensite shows improved deformability compared to the as-quenched martensite.

The core of the heat treated reinforcing bars/wires consist of ferrite and perlite – more ductile but less strong than the martensite. Computerized process control is used to dynamically adjust the many rapidly changing parameters depending on the chemical composition of the steel, the desired grade and size of the reinforcing bar/wire etc. For the larger diameters, small addition of microalloys is usual.

Sometimes it becomes necessary to determine if a particular reinforcing bar/wire, or lot, has undergone proper heat treatment or is only a mild steel deformed bar. Because the two cannot be distinguished visually, the following field test may be used for purposes of identification. A small piece (about 12 mm long) can be cut and the transverse face lightly ground flat on progressively finer emery papers up to '0' size. The sample can be macroetched with nital (5 percent nitric acid in alcohol) at ambient temperature for a few seconds which should then reveal a darker annular region corresponding to martensite/bainite microstructure and a lighter core region. However, this test is not to be regarded as a criterion for rejection. The material conforming to the requirements of this standard for chemical and physical properties shall be considered acceptable.

Fig. 3 Snapshot of the reference from Annex A of IS 1786: 2008 specification

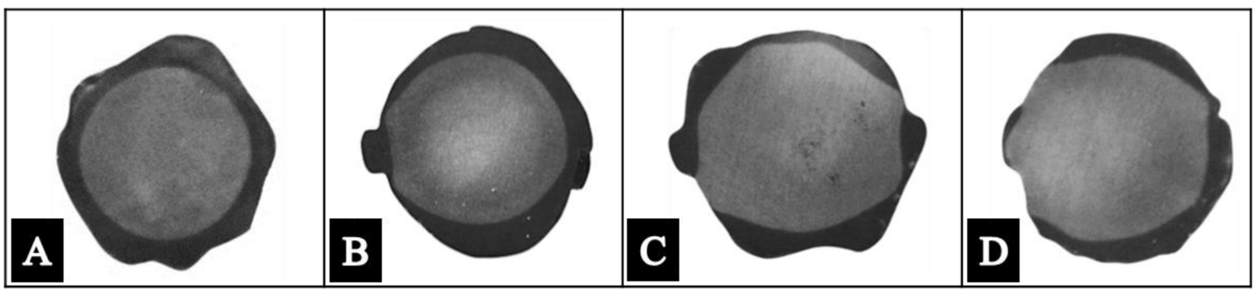


Fig. 4 Typical cross-sections of TMT/QST rebars. (A) Continuous, concentric and uniform, (B) Continuous, eccentric and non-uniform, (C and D) Discontinuous and non-uniform

strengths. This issue associated with the lack of upper limits on yield strength were raised by Rai et al. (2012) as a sign of improvement, the recent draft for the amendment of IS 13920 (2014) recommends to incorporate upper limits in the yield strength for the rebars to be used in seismic applications. Also, the variations in CSPD along the length of a rebar can result in significant variability in the tensile properties along the length of the rebars. In addition, unsymmetrical cross-sections may result in unsymmetrical flexural behavior of rebars. In short, the variations in CSPDs can result in earlier and localized corrosion and variations in mechanical properties, which in turn can lead to unexpected structural behavior of reinforced concrete systems.

1.4 Need for the development of "TM-ring" test method

TM-ring with uniform thickness and FP-core are necessary to ensure uniform mechanical properties and good corrosion resistance of TMT/QST steel rebars. Annex A of IS 1786:2008 briefly discusses a method to assess this using etching techniques. However, this method lacks protocols and specifications required to properly execute the test in a manufacturing plant or construction site and obtain reproducible results. In particular, various steps in the cutting, polishing, and etching processes are intricate and need to be done with care to give reliable and reproducible results. Therefore, a standardized test method to assess the quality of cross-sectional phase distribution (CSPD) is necessary.

2 Research Significance

The cross-sections of steel rebars manufactured in Germany, Italy, Hungary, and Russia and collected/ procured from Germany have exhibited ideal cross-sectional phase distribution (CSPD) with a peripheral TM-ring with uniform thickness and FP-core, as shown in Figure 2. However, many rebars collected from the Indian subcontinent did not exhibit such ideal CSPDs – thereby may exhibit inadequate corrosion resistance and high variability in the mechanical properties. At present, no standardized quality control tests are available to assess the CSPD of TMT/QST steel rebars - resulting in the production of poor quality rebars by many companies. The proposed "TM-ring" test provides specific protocols to obtain reliable and reproducible results – facilitating the stakeholders to perform quality checks at both the steel plant and construction site. It is anticipated that practice of this test will eventually enhance the quality of TMT/QST steel rebars in the Indian subcontinent.

3 Materials and Methods ("TM-Ring Test" Method)

The scope of this study is limited to 8, 12 and 16 mm diameter and 500D Grade TMT/QST steel rebars. A total of 60 rebars from 6 different sources (including the local construction sites and suppliers) in and around Chennai, India and 10 different countries were tested. During these tests, the procedures were fine-tuned and the proposed TM-ring test procedure was developed. Only a few selected results will be presented in this paper, because the focus of this paper is to develop and present the TM-ring test procedure and not to compare the quality of rebars from various sources. For more details on this research, refer Nair (2017).

Following sections provide the details on the proposed TM-ring test method to qualify the CSPD of TMT/QST steel rebars with the following two steps: (i) Specimen preparation and (ii) Identification of CSPD.

3.1 Specimen preparation

The specimen preparation is done in three steps: (i) cutting, (ii) epoxy embedding, and (iii) polishing. A typical ready-to-test specimen is given in Figure 5.

Steel microstructure is sensitive to temperature rise above 200°C (Krauss 2014). Therefore, it is recommended to adopt the following steps with care while cutting and preparing a specimen for standard etching test.

1) Cut a 15 ±2 mm long rebar specimen using a bandsaw or an abrasive cutter with continuous supply of coolant. The use of a coolant is necessary to limit the temperature of steel to a maximum of 100°C. This will avoid any change in the TM and FP phases.
2) Smoothen the sharp edges at the periphery of the cut surface of the specimen by using silicon carbide abrasive sheets (or emery sheets; 80-220 grit size). A metal polishing machine can be used for this.
3) Mould the steel specimen in translucent/opaque cold setting epoxy (single or two component type) with good surface finish and setting time of 10-15 minutes. Translucent or opaque epoxy is recommended so that the top view of a single transverse plane at the polished surface can be

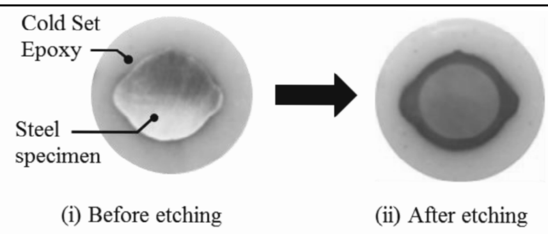


Fig. 5 Typical TMT/QST specimen on etching

imaged/photographed. If the epoxy is transparent, then the transverse ribs from the other transverse planes of the rebar piece will be visible in the top view; this will disturb the cross-sectional image (of the polished surface) and confuse the user in the analysis stage. Also, while mixing/placing the epoxy, avoid air bubbles getting trapped in the epoxy as much as possible to get a good finished surface upon polishing. For this, use an epoxy mix with good flow and tap the mould (while casting) to remove air bubbles and fill the gaps between the inside surface of the mould and the specimen. Also, silicone rubber moulds are recommended to facilitate easy removal of moulded specimen.

4) Coarse polish the molded specimen surface using abrasive sheets (in sequence of 80, 150, 220, 320 and 600 grit sizes). Ensure continuous supply of water or coolant to absorb the heat generated and avoid rise in the temperature of steel specimen. The speed of the belt grinder/disc/abrasive sheet of the polishing machine can be maintained between 150 and 300 rpm.

3.2 Identification of cross-sectional phase distribution (CSPD)

The brief procedure in the Annex A of IS 1786: 2008 instructs to use a 5% nitric acid in ethyl alcohol (hereafter termed 'nital') solution to etch the steel surface and identify the cross-sectional phase distribution (CSPD).

3.2.1 Imaging setup and procedures

It is recommended to standardize the imaging setup and procedures for obtaining reliable and reproducible results. The schematic of the recommended imaging setup is shown in Figure 6 .

The details of the imaging procedures are as follows.

1) Mount a digital camera with minimum specifications of 8MP and 6X optical zoom onto the vertical plate. The camera zoom and movable platform (for placing the specimen) help to focus exactly on the specimen surface.
2) Use a flat and white surface as the movable base platform. Place the specimen with the test surface parallel to the base. User may check this using a standard laboratory leveling tool. If the specimen is kept inclined, then it can affect the grey shade at different locations on the etched surface of the specimen.
3) On the stand, place a camera perpendicular to the horizontal base and focused in-plane with the etched surface. The position of the platform and specimen can be adjusted vertically, as shown in Figure 6 .
4) Place two lamps, as shown in Figure 6, to have a light intensity of 350 to 400 lux near the specimen surface. Use a luxmeter for measuring the light intensity.

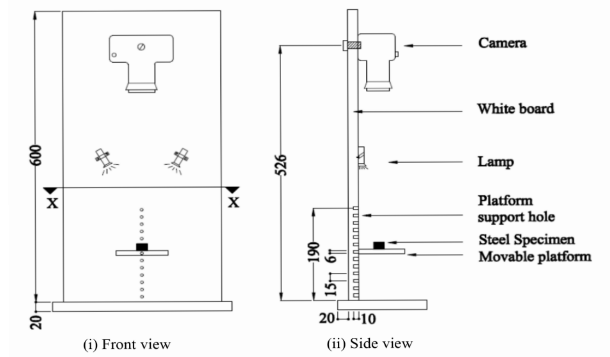


Fig. 6 Imaging Setup

5) Place a measuring scale beside the specimen at the same level of the etched plane (not at the platform level), as shown in Figure 7. This is necessary for the image analysis step - to define the reference locations and scale of measurement.
6) Turn-off the camera flash, turn-on the two lamps, and capture the photograph of the specimen as soon as the nital solution is placed on the steel specimen and until the regions with FP and TM phases are distinguishable with naked eyes. An automated image acquisition system, if any, could help in taking the images and keeping track of the progress of etching and color changes.

3.2.2 Etching procedures

The recommended procedures for etching are given below:

1) Place 2 ml of a 5% nital solution using a micro pipette or syringe over the test surface of steel specimen placed on the movable platform. If the solution is insufficient to flow and cover the entire surface of the steel, then place immediately more solution, as needed.
2) Wait for 5 minutes for the etching to occur and the TM and FP phases to be visible with naked eyes. In some cases, TM-FP transition phase may also be visible.
3) After 5 minutes of etching, place a tissue paper or cloth on the etched surface and allow it to absorb the residual nital solution. Leave the remaining nital solution over the steel surface while imaging, provided the glare from the lights are avoided. In any case, do not wipe the surface, which may remove the etched products (see Figure 7 A).

The TM-ring test method detailed in Sections 3.1 and 3.2 will provide a step-by-step procedure for the technicians at construction sites and QC labs to assess the quality of TMT/QST rebars in the context of CSPD. The general classification of the observations and acceptance criteria is given in subsequent sections.

4 Results and Discussion

Figure 8 shows four typical images of CSPDs of TMT/QST steel rebars. A good quality rebar should exhibit continuous, concentric and uniform TM phase and a core with FP phase (as shown in Figure 4.A). On the other hand, a poor quality rebar could exhibit either of the three defects (i.e., discontinuous, eccentric or non-uniform) or a combination of these as shown in Figure 4. These defects could form due to improper quenching in the In-Line QST treatments. This study proposes to broadly classify these defects as follows:

(a) Eccentric and non-uniform TM-phase: Cases where the TM-phase at the periphery is continuous but eccentric; and have non-uniform thickness.
(b) Discontinuous and non-uniform TM-phase: Cases where the TM-phase at the periphery does not form a complete ring and is discontinuous at one or more locations (i.e., both FP and TM phases are exposed at the surface); and have non-uniform thickness.

Based on the observations, Section 4.1 discusses the possible outcomes of the "TM-ring" test and their evaluation details.

4.1 General classification of results of "TM-ring" test

The Reference Cases A, B, C, and D in Figure 8 indicate four possible outcomes from the "TM-ring" test. Case A indicate good quality, whereas Cases B, C, and D indicate poor quality.

Case A in Figure 8 indicate an ideal rebar showing a continuous, concentric, and uniformly thick TM-ring. Through the laboratory tests on various steel rebars collected from the market, it was found that this kind of perfect TM-rings are mostly seen in large diameter rebars and lacking in rebars with less than 16 mm diameter. Moreover, such small diameter rebars are used as stirrups with smaller cover depth than that of primary reinforcement with larger diameter. This hints that better quality control is required for such smaller diameter rebars.

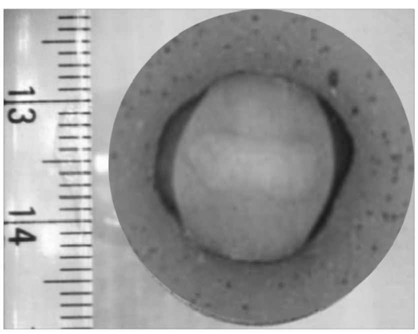


Fig. 7 Image taken with measuring scale beside test sample

Case B in Figure 8 is a case of continuous, eccentric, and non-uniform TM phase. The ring thickness is very small at two regions on the left side in the image. This could probably occur if the coolant temperature or pressure is not uniform along the circumference. As a result, differential temperature gradient occurs forming TM-ring with non-uniform and inadequate thickness at some regions. These types of defects were mostly found in 12 and 16 mm diameters. On the contrary, over-quenching at specific points can form TM-ring with non-uniform and more than adequate thickness at some regions.

Case C in Figure 8 shows a non-uniform TM-phase with scattered discontinuities. This cannot be defined as a case of concentricity. This could occur when the quenching hardware fails (e.g., clogged nozzle) to work at some locations over the surface of the rolled rebar in the cooling stage. Theoretically, when the minimum thickness of the ring in Case B becomes zero, it forms a discontinuity.

Case D in Figure 8 shows a discontinuous and non-uniform TM region- with a relatively longer discontinuity (seen to the left side) when compared to Case C. The quenching and self-tempering of rebars require better quality control to avoid this.

Discontinuous TM-rings (Cases C and D) were mostly observed in 8 and 12 mm diameter rebars. However, note that such defective bars could also exist in 16+ mm diameter rebars. It is generally observed that the relative thickness of TM-ring increases with an increase in diameter of the rebar, reducing the chances for defects in TM-ring. Note that this increase in TM-phase, will in turn result in a reduction in the FP-phase. The impact of this on the tensile strength and ductility needs to be studied. It is recommended that the CSPD must be assessed for at least one specimen from each rebar lot. Therefore, a feasible and easily employable acceptance criteria for TMT/QST rebars is necessary as part of the 'TM-ring' test.

4.2 Acceptance criteria for TMT/QST steel rebars subjected to "TM-ring" test

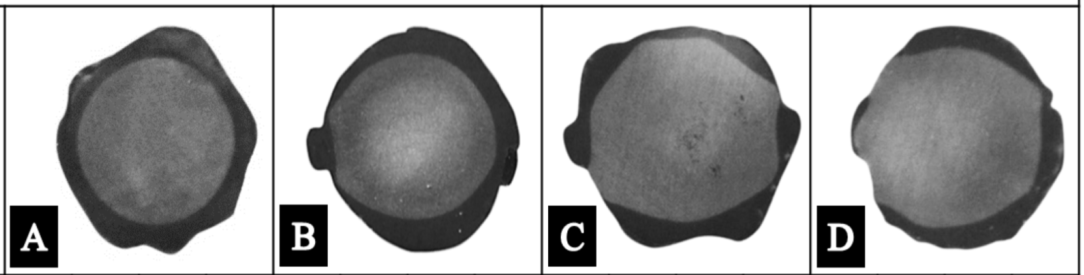
Figure 8 shows the proposed 2-Level acceptance criteria: (i) Level 1: Visual Analysis and (ii) Level 2: Thickness analysis. Level 2 assessment is done only if the rebar is 'accepted' in Level 1.

4.2.1 Level 1 Acceptance Criteria: Visual analysis

Level 1 (L1) acceptance criteria is based on a qualitative visual analysis of the images obtained from Section 3.2.2. The L1 criteria will help categorize the

Datasheet for ‘TM-Ring’ test

REFERENCE CASES



	A				B				C				D			
L1	Y	Y	Y	Y	Y	Y	N	N	Y	N	N	N	Y	N	N	N
L2	Y		Y		-				-				-			
	Accepted				Rejected				Rejected				Rejected			

LEVEL 1 (L1) ACCEPTANCE CRITERIA		
No.	**Question**	**Answer (circle one)**
1	Is a dark grey peripheral region and light grey core seen?	Yes / No
2	Does the dark grey peripheral region form a continuous outer ring?	Yes / No
3	Are the dark grey peripheral region and light grey core concentric?	Yes / No
4	Is the thickness of the dark grey peripheral region uniform?	Yes / No
Decision		
If all the answers are **‘Yes’**, then accept the rebar lot		
If any one or more answers are **‘No’**, then reject the rebar lot		

LEVEL 2 (L2) ACCEPTANCE CRITERIA		
No.	**Observations**	**in mm**
1	Diameter of rebar, D	
2	Measured thickness of TM, t_{TM}	
No.	**Question**	**Answer (circle one)**
1	Is $t_{TM} \geq 0.07$ D ?	Yes / No
2	Is $t_{TM} \leq 0.10$ D ?	Yes / No
Decision		
If all the answers are **‘Yes’**, then accept the rebar lot		
If any one or more answers are **‘No’**, then reject the rebar lot		

Fig. 8 Datasheet for “TM-ring” test

image into one of the cases given in Figure 8. The user is instructed to check the formation of a ring and core on etching and evaluate the continuity, uniformity and eccentricity of the TM-phases formed. If the answer for all the four questions in the first table in Figure 8 are 'Yes', then the rebar lot can be 'accepted' for use. If any one or more answers are 'No', then the rebar lot must be 'rejected' for use. It is also recommended to polish adequately and repeat the "TM-Ring" test on the same specimen surface – to confirm the visual observations.

4.2.2 Level 2 Acceptance Criteria: Thickness analysis

The Level 2 acceptance criteria shall be used only for the rebars 'accepted' in the Level 1. In Level 2, the thickness of TM phase (darker region) in the image of the etched surface is measured/analyzed. Any suitable instrument (e.g., Vernier Caliper, Crack Gauge, etc.) or an image analysis software could be used for this purpose. This study used ImageJ®, which is a free software developed by National Institute of Health (NIH), USA. As per Markan (2005) and Ambuja (2005), the recommended area of "TM-ring" is 25-53% of the rebar cross-sectional area. The corresponding minimum and maximum thickness of the "TM-ring" for 25% and 35% area of TM, respectively, are calculated as follows.

Minimum expected thickness of TM $t_{TM,min}$ =
where, D = Nominal diameter of rebar, and

$$\frac{D-D_{FP}}{2}=\sqrt{\frac{A}{\pi}}-\sqrt{\frac{A_{FP}}{\pi}}=\sqrt{\frac{A}{\pi}}-\sqrt{\frac{0.75A}{\pi}}$$

$$=0.134\sqrt{\frac{A}{\pi}}=0.134\sqrt{\frac{\left(\frac{\pi D^2}{4}\right)}{\pi}}=0.07D$$

D_{FP} = Diameter of FP core area.

Similarly, the maximum expected thickness of TM $t_{TM,max}$ = 0.1 D.

Therefore, for all the rebar sizes, the measured thickness of TM (t_{TM}) is recommended to be between 0.07D and 0.1D. In short, a rebar can be 'accepted' if the t_{TM} is between 0.07D and 0.1D, where D is the designated or nominal diameter of the rebar. This checks if a rebar with continuous TM-ring has been quenched properly to be acceptable. These acceptance limits on thickness of TM phase have been established based on the expected cross-sectional area of TM and FP phases [Markan (2005) and Ambuja (2005)]. However, the evaluation of thickness is comparatively easier than cross-sectional area; hence, this paper suggests as an equivalent acceptance criteria based on minimum and maximum thickness of TM phase.

These details have been included with illustration as a data sheet in Figure 8 . The datasheet could be used by an engineer at steel plant or construction site to check the quality of TMT/QST steel rebars. L1 criteria is recommended for QC engineers at construction sites. L1 followed by L2 criteria is recommended for steel rebar manufacturing plants, which could help them to determine the right quenching parameters to get the desired quality.

4.3 Possible errors in the testing

Figure 9 gives possible errors that a user could face in the TM-ring test method.

These are mentioned beforehand for the user to understand the errors and avoid them during the "TM-ring" tests. There are four results given in Figure 9 and discussed below.

- Result I shows the stains (which formed the dark ring) being removed while wiping the excess solution (by hand). In such cases, the user is advised to immediately wipe/clean the surface with a wet and soft cloth, polish the surface again, and repeat the "TM-Ring" test.
- Result II occurs under inadequate and inappropriate polishing. Partial or most of the surface area may remain dark. At the same time, some portion get etched and shows the colour difference. It is instructed to polish the specimen again and repeat the testing.
- Result III could arise when the concentration of nital is too high (say, more than 10%). Note that, if the nital solution is not stored properly, the alcohol part could evaporate and the concentration could increase than expected.
- Result IV can occur when the test specimen is cut (from a rebar piece) without using any coolant and the cross-section gets damaged. It is instructed to procure a new specimen and continue the test. The user shall also extract a new test specimen from a distance of 3 times the diameter from the cut end (or heat affected zone) of the rebar. Also, ensure that a coolant is used for all the cutting procedures.

a) Wiping the etch stain b) Poor polishing c) Heat damage when cut without coolant

Fig. 9 Erroneous observations due to inappropriate/ inadequate etching procedures

5 Practical Applications

It is found that the TMT/QST steel rebars with in appropriate or defective TM-phase at the periphery are available in the market. The "TM-Ring" test will show whether a TMT/QST rebar has undergone adequate heat treatment. If signs of inadequate treatment are found, then the technicians at the steel plant could control the quenching line parameters to avoid the possible defects in rebars. As part of this quality control, the paper also suggests the use of "TM-ring" test as a field test method. The "TM-ring" test could be performed at the construction site laboratories and the material testing laboratories - to assess and ensure that the rebar lots being used are meeting the acceptance criteria developed.

6 Summary and Conclusions

Within its scope, the paper introduces a potential quality control issue in the manufacturing of TMT/QST steel rebars in the Indian market. The presence of defects in the peripheral tempered martensite (TM) ring and ferrite-pearlite (FP) core, respectively, in TMT/QST steel rebars of 8, 12 and 16 mm diameters. The potential defects were classified broadly into discontinuous, non-uniform TM-ring and eccentric FP core.

A "TM-ring test" protocol has been developed/documented to evaluate the cross-sectional phase distribution (CSPD) in TMT/QST steel rebars. The test protocol includes guidelines for specimen extraction, preparation, macroetching, analysis, and documentation of results. The developed "TM-Ring" test could be used by the technicians at the steel plant and construction sites to assess the quality in terms of CSPD. A 2-level acceptance criteria have also been provided.

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