# Identification of the Microstructure of TMT rebars and its impact on Mechanical properties

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## Abstract

Steel is essential to industrial progress, and understanding its heat treatment processes is crucial for material optimization. This study investigates the microstructure of TMT rebars under various heat treatments (annealing, normalizing, quenching) and their impact on mechanical properties such as ductility, hardness, and strength. Microscopic observations reveal phase transformations such as ferrite, pearlite and martensite, and their relationship with mechanical performance is examined. The Hall-Petch equation is applied to determine the mechanical strength of the steels. Samples were observed under a 500x magnification microscope after polishing and etching to expose microstructural structure. In annealed TMT rebars, the individual size of ferrite increases, resulting in increased ductility. Finer grains observed at lower temperatures lead to higher hardness, whereas coarse grains observed at higher temperatures lead to better machinability of TMT rebars. Similar to annealing, in the normalization process of TMT rebars, as the temperature rises, the grain structure becomes fine-to-coarse. Quenched steel is characterized by the formation of martensite, which signifies high hardness, strength, and brittleness. These results show how important heat treatment is in determining a material's characteristics. Different factors, such as cooling rate, heat treatment method, and material composition, impact our understanding of steel's properties.

Keywords: *Etching, Heat Treatment, Microscopic, Microstructure*

## 1. Introduction

Metal has played an important role in modern society advancement and transformation. Among all the metals steel has been a pillar for shaping modern society. Thermo-Mechanically Treated (TMT) Fe500 D rods are a type of steel reinforcement bar used in the construction industry because of their mechanical properties, such as high tensile strength and ductility. Fe500 D is a grade of TMT bar that is manufactured to meet the high demands of infrastructural development, especially in reinforced concrete structures. The "500" in Fe500 denotes the yield strength of the bar in Megapascals (MPa), meaning these bars can withstand stresses of up to 500 MPa before rupture (Kumar, 2020). The mechanical properties of TMT Fe500 D bars, such as high strength, corrosion resistance, and ductility, make them best for use in buildings, bridges, and other infrastructure projects that require durability and reliable reinforcement (Singh et al., 2019). Moreover, the use bars in earthquake-prone zones are popularity due to their ability to withstand dynamic loads, which is important for ensuring the structural safety of buildings in earthquake-prone regions (Choudhary, 2023).

Heat treatment processes like annealing, tempering, quenching, and normalizing are used to change the microstructure of steel to gain desired mechanical properties (Mitchell, 2016). Ferrite and pearlite exhibit different properties due to their distinct microstructures. Ferrite, a Body-Centered Cubic (BCC) phase, contributes to ductility, while pearlite, a lamellar structure of ferrite and cementite provides a balance between strength and ductility. Martensite, which forms during quenching is a hard and strong phase but tends to reduce ductility. (Bhadeshia, 2001). Grain size is an important factor in determining the mechanical strength of the steel. According to Hall-Petch's relationship, finer grains contribute to higher strength due to the increased number of grain boundaries, which restrict the movement of dislocations (Hall, 1951). The Hall-Petch equation is

$$\sigma_y=\sigma_o+k\cdot d^{1/2} \qquad (1)$$

where,

$\sigma_y$ = yield stress; $\sigma_o$ = friction stress; k= Hall-Petch slope; d= Average grain diameter

From equation (1), the diameter of the grains directly proportional to the yield stress of materials. Thus, fine-grained materials are stronger than coarse-grained ones.

The microstructure of martensite is needle-like in structures that are highly deformed. The material's hardness is influenced by the dislocation density. In martensitic steels, the higher the dislocation density, the greater the hardness. The grain size of martensite alters its hardness, finer grains result in harder steel. (Khan, 2011). Microstructure analysis using ImageJ revealed significant variation in martensite, ferrite, and pearlite compositions in mild steel, and bars under different cooling methods. Ice quenching maximized martensite formation, enhancing hardness but reducing ductility. Normalizing promoted pearlite formation, increasing toughness. The findings Highlight the impact of cooling rate and etching technique on mechanical properties. (Amit Kumar Mandal, 2024). Nital is used for examining a different type of steel, like low-carbon steels to high-strength, alloyed steels. In low-carbon steels, Nital reveals the ferrite and pearlite microstructure, for alloy steels, Nital helps in revealing the presence of phases like martensite, which have relations with the mechanical properties of steel (Krauss, 2005).

## 2. Materials and Methods

A 20 mm diameter Fe 500D grade TMT rebar (500 XD) was used in this study. The rebar sample was transfer to a diameter of 1.6 cm and a height of 2.5 cm using various machining processes for easy gripping and handling. The prepared samples were heated to 800°C, 900°C, and 1000°C in a muffle furnace and held at each temperature for a certain duration to allow for temperature retention. The sample was hold for 10 minutes, 30 minutes, 30 minutes on the temperature 800°C, 900°C, and 1000°C respectively. After heating, the sample was cooled to room temperature 28°C through different mediums including furnace cooling, air cooling, water quenching, oil quenching, and ice quenching.

The cooled sample was then polished using a Handimet 2 roll grinder and a Lab pol Duo twin grinder with different grades of sandpaper to achieve a smooth surface. The polished surface was etched using a Nital etchant (mixture of 10% conc. $HNO_3$ and 90% ethanol) for a certain time interval. The Nital etchant reacts with the microstructures present on the surface, resulting in dark pearlite and white ferrite due to their different reaction times with the etchant. The etching duration differs based on the heat treatment process and was determined through a hit- and- trial method.

The etching, the sample was cleaned with distilled water and prepared for microscopic observation. An optical microscope with a 500x magnification was used to observe the microstructure. The most cleared images were captured using a camera for further analysis. The size, distribution, and arrangement of pearlite, ferrite, and martensite were analyses with naked eyes, and the corresponding mechanical properties were determined.

## 3. Result and Discussion

The observation of different samples under an optical microscope revealed variations in the pattern, arrangement, and size of ferrite, pearlite, and martensite, depending on the heat treatment process. The images observed under the optical microscope had a diameter of 0.036 mm. The darker patches seen were pearlite, the bright patches were ferrite whereas the needle like structure seen on quenched sample was martensite.

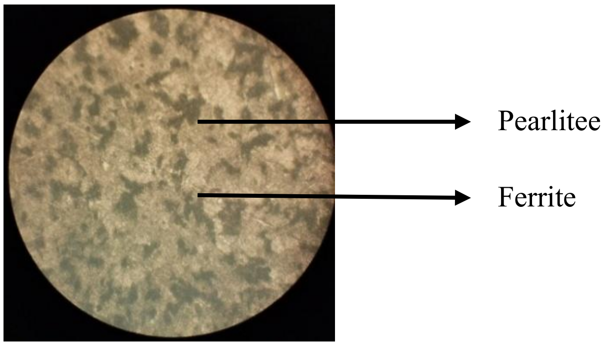



Fig. 29: Microstructure of annealed TMT steel at 900°C

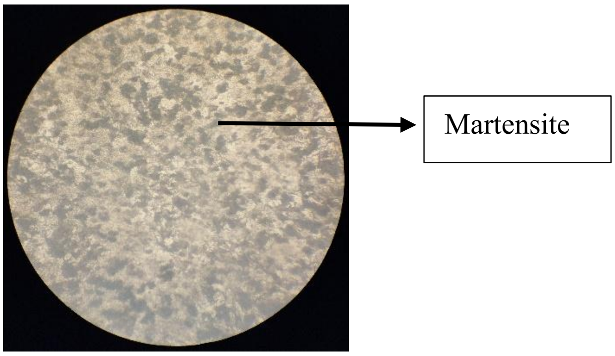



Fig. 30: Microstructure of water quenched TMT steel at 900°C

## 3.1 Non-heat-treated TMT rebar

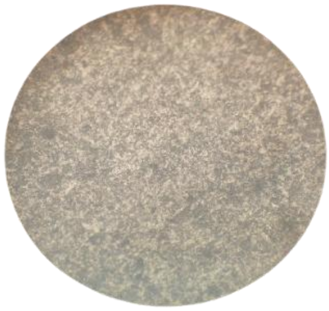
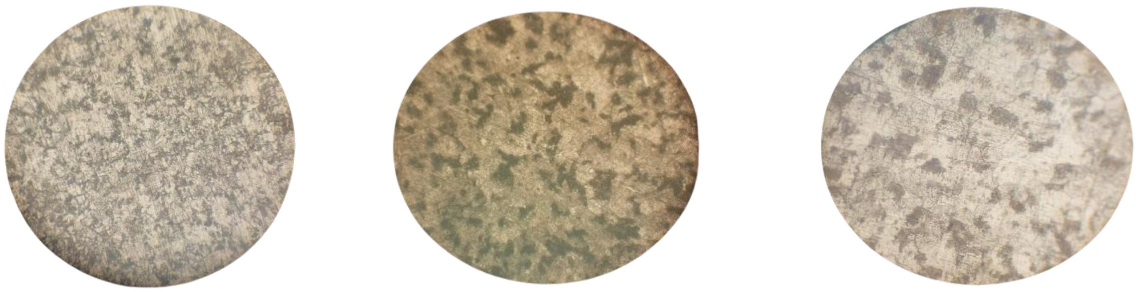


Fig. 31: Microscopic view of TMT rebar

From Fig. 3, the size and arrangement of ferrite and pearlite grains were observed to be small, fine, and more compact. A smaller and more compact grain structure in steel improves mechanical properties, such as increased strength, as explained by the Hall-Petch relationship, the finer the grain size higher the mechanical strength. Finer microstructures create more obstacles to dislocation motion, resulting in better ductility.

## 3.2 Annealed TMT rebar



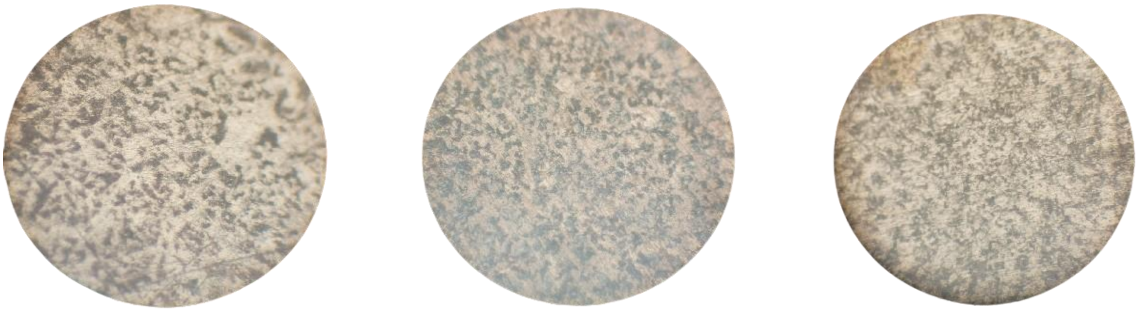
(a) (b) (c)

Fig. 4: Microstructure of annealed TMT rebars at a) 800°C, b) 900°C and c)1000°C

From Fig. 4, during annealing at 800°C, ferrite and pearlite grains become more refined. At 900°C, pearlite begins to form more rounded particles alongside ferrite. Compared to other temperature ranges, annealing at 1000°C results in larger ferrite grains and more rounded pearlite. As the grain size of ferrite and pearlite increases during the annealing process, the ductility of the TMT bar improves. However, the coarser microstructure leads to a reduction in hardness and strength. The grain size increases as the heating temperature rises from 800°C to 1000°C resulting the higher ductility on higher temperature.

## 3.3 Normalize TMT rebars

From Fig. 5, At 800°C, microstructural changes occur, similar to a low-temperature annealing process. Normalizing at 900°C results in a fine mixture of ferrite and pearlite. Air cooling the sample from 1000°C to room temperature leads to the formation of even finer ferrite and pearlite.

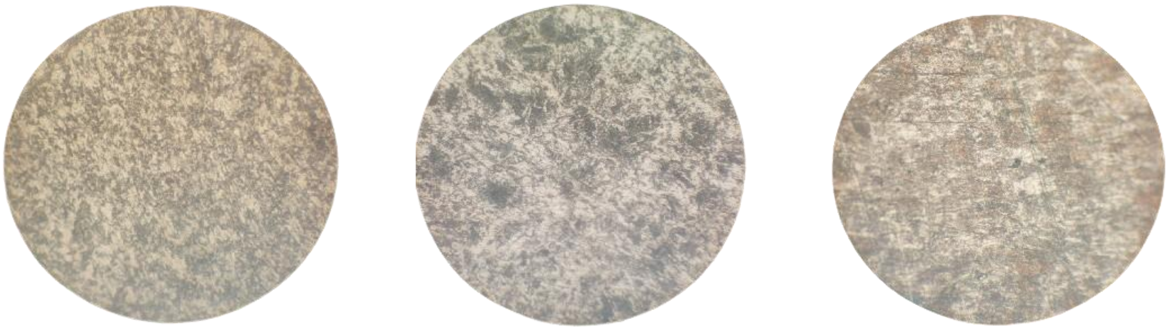


(a) (b) (c)

Fig. 5: Microstructure of normalized TMT rebars at a) 800°C, b) 900°C and c) 1000°C

As the normalizing process refines the grain structure, it increases strength according to the Hall-Petch relationship while decreasing ductility, as finer and more compact grains oppose dislocation movement. The mechanical strength of the bars increased as the heating temperature rise from 800°C to 1000°C as finer microstructure is formed at higher temperature.

## 3.4 Oil quenched TMT rebars

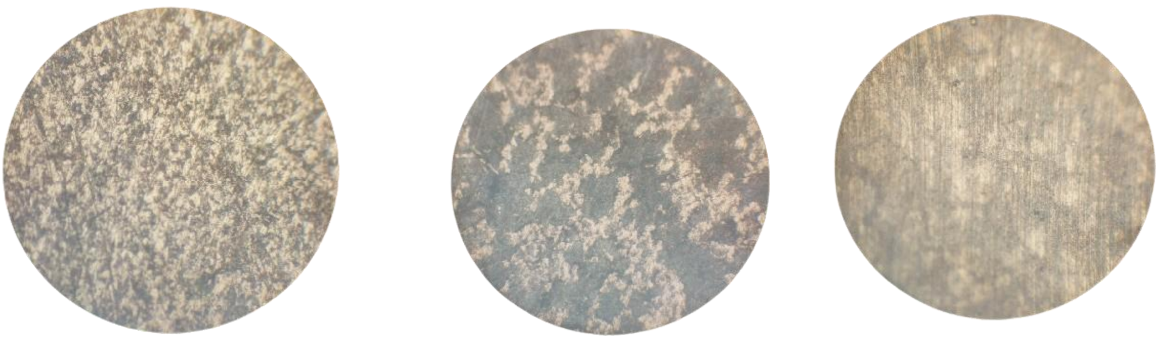


(a) (b) (c)

Fig. 6: Microstructure of oil quenched TMT rebar at a) 800°C, b) 900°C and c)1000°C

From Fig. 6, Oil quenching from 800°C results in martensite with minimal retained ferrite and pearlite. During oil quenching from 900°C, a predominantly martensitic structure forms, along with some retained pearlite and ferrite. The grain size of martensite appears to increase when oil quenched from 1000°C. As a result of the martensitic transformation, the hardness and brittleness of the TMT rebars increase. As the formation of martensite increase with rise in temperature resulting for obstacles to dislocation motion. Thus, the hardness of the bars increases as the temperature increase form 800°C to 1000°C.

## 3.5 Ice quenched TMT rebars

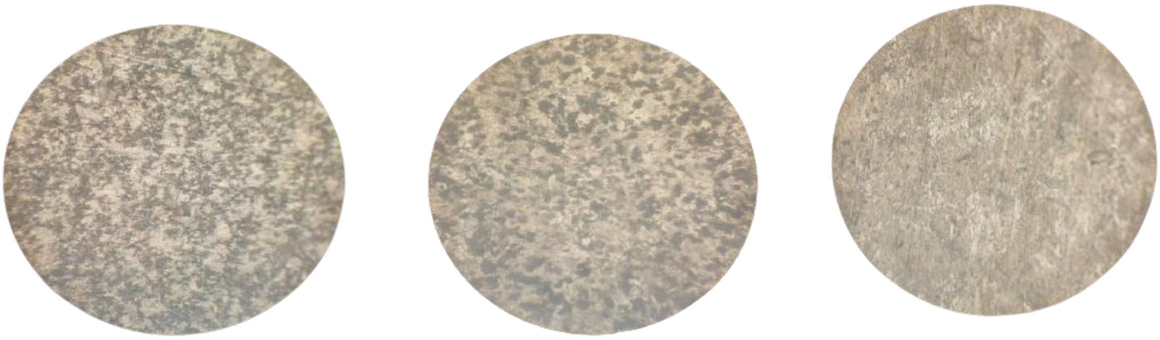


(a) (b) (c)

Fig. 7: Microstructure of ice quenched TMT rebars at a) 800°C, b) 900°C and c)1000°C

From Fig. 7, During ice quenching from 800°C, martensite, along with significantly refined pearlite and ferrite, is formed. At 900°C, ice quenching results in predominantly martensitic formation with fewer ferrite and pearlite phases. A more complete transformation to martensite occurs during ice quenching from 1000°C compared to lower temperatures. The increased formation of martensite makes the TMT rebars harder, less ductile, and more brittle. As the transformation of the ferrite and pearlite into martensite increases during quenching from temperature 800°C to 1000°C the ductility and mechanical strength of the bar decrease with increasing on hardness.

## 3.6 Water quenched TMT rebars



(a) (b) (c)

Fig. 8: Microstructure of water quenched TMT rebars at a) 800°C, b) 900°C and c)1000°C

From Fig. 8, During water quenching at 800°C, martensite begins to form; however, the transformation is not complete or uniform. When quenched at 900°C, martensite with finer grains, a more uniform structure, and reduced amounts of ferrite and pearlite is formed. Quenching at 1000°C results in the formation of larger and coarser martensite. These changes in microstructure increased hardness and strength but decreased ductility, making the sample more brittle.

The comparison chart of microstructure, mechanical strength, ductility, hardness of the TMT rebars after different heat treatment process are on Table 1.

Table 1: Comparing mechanical property of different heat-treated sample

| **Property** | **Normal TMT rebars** | **Annealing TMT rebars** | **Normalizing TMT rebars** | **Quenching TMT rebars** |
|---|---|---|---|---|
| **Microstructure** | Ferrites and pearlites | Coarser ferrites and pearlites | Finer ferrites and pearlites | Martensite along with some ferrites and pearlites |
| **Strength** | Moderate | Low-Moderate | High | Very high |
| **Ductility** | High | Very high | Moderate-High | Low (lowest for water quenching) |
| **Hardness** | Moderate | Low-Moderate | Moderate | Very high (highest for water quenching) |

## 4. Conclusion

The mechanical properties of TMT rebars can differ with respect to various heat treatment processes. In conclusion, annealing softens the TMT rebars and increases ductility. Normalizing refines the grain structure and increases strength. Martensite is formed during the quenching process, resulting the TMT rebars becoming harder and more brittle. Thus, the change on size, distance, composition of microstructure like ferrite, pearlite, martensite, influence the mechanical property like harness ductility and mechanical strength of the TMT rebars. These findings can be directly used in real-world manufacturing processes to optimize the mechanical properties of rebars used in construction, ensuring better performance under stress and enhanced durability. Future studies could explore the impact of cooling rates in more detail or test other variations in heat treatment to achieve even finer control over the microstructure of TMT rebars. Additionally, improvements in methodology, such as using advanced tools or simulation techniques, could provide better insight into grain growth mechanisms and enhance the understanding of heat treatment effects.

## References

Amit Kumar Mandal, D. M. (2024). Quantitative Comparison of Grain Structure in Heat Treated, Nital-Etched Mild Steel and TMT Bars. OODBODHAN, 7, 71–76. doi:https://doi.org/10.3126/oodbodhan.v7i1.75770

Bhadeshia, H. K. (2001). Bainite in steels: Transformation, microstructure, and properties. Institute of Materials, 2, 451.

Choudhary, R. &. (2023). Influence of quenching media on phase transformation in TMT bars. Journal of Mechanical Engineering and Materials, 68(1), 77-92.

Khan, A. &. (2011). Microstructure and Hardness Relationship in Martensitic Steel. Materials Science and Engineering: A, 528(17), 5412-5421.

Krauss, G. (2005). Steels: Processing, Structure, and Performance. . ASM International.

Kumar, A. S. (2020). Microstructural analysis and mechanical performance of thermomechanically treated rebars. International Journal of Metallurgical Research, 62(1), 55-68.

Mitchell, T. M. (2016). Engineering metallurgy: Applied physical metallurgy. Butterworth-Heinemann.