Analysing strength, hardness and grain-structure of 0.2%-C steel specimens processed through an identical heating period with different continuous transformation rates

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Abstract
The present work deals with improvement of mechanical properties and refining the microstructure of low carbon steel (0.2%-C) after applying heat treatment techniques. For the purpose, five different samples were taken under study. First sample was kept in 'as received' condition and other four samples were undergone into heating process in an Induction furnace. The holding temperature of all the four samples were kept common i.e., 850 °C for a fixed period of 2.5 h. Then, these four samples were cooled into four different cooling media i.e., Air, Water, Oil, and Furnace. All the samples were in the form of rods with 195 mm length and 32 mm diameter. The universal testing machine was used to determine the tensile strength of all the samples. Rockwell hardness tester was used to find the hardness of samples. The microstructural variation was analysed through an optical microscope. All the results were analysed and compared with 'as received' sample. The Oil cooled sample showed the highest tensile strength of 585 MPa. The microstructural orientation of oil cooled sample i.e., bainite + fine lamella of ferrite and cementite, provides a good hardness, strength, and toughness to the steel. In addition, XRD and fractography analysis of the samples were also carried out.

1. Introduction

Low carbon steel is widely used all over the world due to its high range of tensile strength, compressive strength, toughness, and bending strength. It possesses high amount of ductility which makes it more useful in construction area. The typical values of physical properties of a low carbon steel are given in table 1. The carbon content in low-C steel varies from 0.08%–0.25%. Less carbon amount reflects high ductility and toughness value. Low carbon steel is widely used as thermo-mechanically treated (TMT) rods in construction of building, bridges, and heavy structures. The properties of the steel can be varied by applying different kinds of heat treatment methods. The fundamental of heat treatment has been discussed in below sections.
1.1. Heat treatment
Heat treatment is a method of heating the metal up to a desired level of temperature; holding the metal at this temperature for a period and then cooling it to get desired microstructural changes for an improved physical property. Heat treatment techniques are old but nevertheless commonly used strategies in enhancing the characteristics of steel. In heat treatment of metals, defining the range of temperature variation is utmost important. Temperature selection is done with a knowledge of phase diagram of metal. In case of steel, observation of Fe-C phase diagram is necessary prior to heat treatment. The minimum temperature of phase transformation, i.e., lower critical temperature is 727 °C for the steels (both hypo- and hyper-eutectoid). But the upper critical temperature range varies with carbon content. Several heat treatments approaches are used to improve the characteristics of steel. Features like tensile strength, durability and other mechanical properties of a material can be changed with the use of heat treatment with no simultaneous change in the look of the given material. The reason why these changes are observed is because heat treatment alters the percentage weight of phases and the size of grains of the specimen [2].

Three main procedures of heat treatment which modify the mechanical attributes of a metal or metal alloy are: normalizing, annealing, and hardening. Normalizing is a heat treatment procedure wherein the steel alloy is first heated till austenitic temperature zone for 1–2 h and then cooled in atmospheric air till room temperature. It disposes off the undesirable free carbide present within the sample received. Also, a pearlite matrix is achieved in steel as final microstructure. For improving the strength and wear resistance, steels are generally hardened. Hardening is a procedure in which the metal is first heated to recrystallization temperature for a duration of time and later quenched by either water or oil. Throughout the heating of steel in hardening technique, the metal is heated enough that the formation of austenite takes place. In annealing procedure, the steel or alloy of steel is heated for a period and later cooled very slowly. Additionally, it is performed to refine the grains structure to ferrite-pearlite microstructure. This system is typically used to achieve good elongation and high tensile strength.

1.2. Continuous cooling transformation
After heating and soaking the steel in preferably austenitic zone, cooling rate is decided as per desired final microstructure. In continuous cooling transformation process, steel is allowed to cool in single medium to get the final structure. Based on cooling rates, different curves can be obtained which indicate the beginning and end of transformation. In general, a very slow cooling rate provides a full transformation of austenite to coarse pearlite. If the cooling rate becomes a bit faster, the fine pearlite will be the result. In some cases, cooling rate can be so adjusted that austenite is allowed to enter the transformation zone with a partial conversion into pearlite along with another structure called martensite. In another case, a rapid cooling rate can be chosen so that austenite couldn’t enter the transformation zone resulting in 100% martensite formation [3].

Many research works have already been done in this area in past 10–15 years. Some of the previous research works are summarized here: In the research performed by Olabi and Hashmi, it was revealed that the temperature of 650 °C was the most effective in reducing the residual stresses. Different mechanical and microstructure characteristics were seen when low-carbon steels were passed through varied voltage during heat treatment. The Vickers hardness values have been noted three times better in the metallic samples when voltage was a part of the heat treatment [4]. With varying cooling rates, microstructures of different types of steel differ with each other and this was observed by Calik (2009). Additionally, a direct relationship was seen between the hardness and the cooling rates. Another type of steel, namely D2, was cold treated in a temperature range of −120 °C to −150 °C and the dimensional steadiness was achieved at −150 °C [5]. Oil quenching and tempering process was done by Htun et al (2008) for property advancement of high steel. After heating the steel

| Properties                      | Metric     |
|---------------------------------|------------|
| Density                         | 7.88 g/cc  |
| Hardness, Brinell               | 162        |
| Ultimate tensile strength       | ≈700 MPa   |
| Yield Strength                  | ≈365 MPa   |
| Elongation at Break (in 50 mm)  | 16.2%      |
| Reduction in Area               | 40.1%      |
| Modulus of Elasticity           | 201 GPa    |
| Bulk Modulus                    | 139 GPa    |
| Poisson’s Ratio                 | 0.289      |
| Shear Modulus                   | 79 GPa     |

Table 1. Physical properties of Low carbon (AISI 1045) steel [1].
samples at 870 °C followed by quenching in oil, hardening could be done in steel. After tempering the sample at 450 °C–550 °C, martensite along with retained austenite were defined. Hardness and ultimate tensile strength had an inverse relationship with tempering time whereas ductility had a direct relationship with both tempering time and temperature [6]. According to the study done by Xian et al (2012), wear resistance of steel had a direct relationship with the austenitising temperature in the range 920 °C to 1120 °C. From 1120 °C to 1220 °C, wear resistance was seen to be depreciating [7]. After annealing, normalising and hardening, the three-heat treatment process, hardness for the mild steel was studied by Hossain et al (2014). It was observed that annealed specimen with ferrite microstructure had the least hardness value [8]. As per George et al (2018), tensile strength was maximum for brine quenched specimen and was least for annealed one. In the same way, the maximum and least hardness value were seen in brine quenched and annealed specimen. But in the case of toughness, annealed had more than that of quenched specimen. In A-36 (mild steel), quenching had a positive impact on tensile strength [9]. For EN-9 steel, different mechanical properties were noted before and after the heat treatment. It was brought into notice that there was a positive impact in hardness after heat treatment. Percentage elongation was seen for the annealed one. The impact strength of normalized sample was maximum whereas it was least for hardened sample [10]. After performing tempering heat treatment on a chromium cast iron, Guo et al (2016) recorded the microstructure and mechanical properties of it. On heating it up to a range of 1020 °C, metal carbides (M7C3) were found in austenite. The hardness of HCCI gets high enough by rapid cooling. Tempering the quenched specimen helped in decreasing the hardness and increasing the impact toughness [11]. In a study, after performing annealing, ultimate tensile strength had an upward result but there was opposite result for ductility [12]. In the dual phase heat treatment done by Gurumurthy et al (2018), combination of ferrite and bainite were observed under the microscope when the specimen was heated for two hours below its critical temperature followed by immersion in sodium nitrate salt bath and later decreasing its temperature in the atmospheric air till room temperature. A combination of ferrite and martensite was recorded when the salt bath was given to the sample for just 10 s [13]. In an experiment done by Hofinger (2019), it was found that a decrease in carbon content reduced the formation of large and brittle carbide [14]. Dewangan et al (2020, 2021, 2022) have done an extensive work on heat treated low-carbon steel for its property enhancement and grain structure refinement. Water quenched products were always reported with high value of ultimate tensile strength but with the loss of yield strength and extension prior to failure. The micrographs were in good relationship with the mechanical behaviour [15–18]. Some of the researchers have taken other grades of steel like nanostructured P91B under study. Various mechanical properties like hardness, creep, micro-deformation etc have been simulated in heat affected zone of the welded plates [19–21].

This work analyses the effect of heat treatment on mechanical property enhancement or modification in low-carbon steel samples. In this study, microstructure, fractography, and XRD analysis of steel were also carried out along with the mechanical tests. The changes in the microscopic level and in the physical properties

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Figure 1. XRD analysis of steel sample used under study.
are recorded after the specimens have gone through three heat treatment process namely: - annealing, hardening, and normalising.

Fractography is a way of examining the fractured surfaces of a specimen provided. By studying or knowing about the features of the fractured surface, one will be able to determine the reason for the failure. Fractography can also be used to generate and study the crack growth model behaviour. Because of the better resolution and larger degree of view as compared to optical microscope, Scanning Electron Microscope (SEM) can show a better topographical feature of the fractured surface.

2. Methodology

2.1. Material selection
The low-carbon steel (0.2%-C) was selected as workpieces for this experimental work. Five such pieces in the form of rods with 195 mm length and 32 mm diameter were taken. The surface of the rods was finished by using sandpapers of 100 grit size. The reason for selecting cylindrical rods was an easiness to prepare the test specimens for tensile strength, hardness, and microstructure analysis. The average physical properties of the steel under study are already discussed in table 1. The elemental and phase analysis of steel sample, used under study, was

Figure 2. Heat treating and cooling of different rods; smoothening of heat treated rods by turning process.
analysed in x-ray diffraction technique to know the basic constituents of that. By using x-ray generator of 40 kV, 50 mA capacity, we came to know that the sample had shown mainly two peaks at the 2θ value of 45° and 65°. Both the peaks are indicating the Iron is in [110] and [200] planes. In addition, a small peak was also observed at 31° angle which could be recognised as cementite phase. The XRD image is shown in figure 1.

2.2. Heating, holding, and cooling of steel samples
Four cylindrical rods were put inside an induction furnace for heating them for 2.5 h at an elevated temperature of 850 °C. One rod was kept in as received condition in which no physical changes were done. This sample was considered as standard on the basis of that heat-treated samples would be analysed. The holding time of 2.5 h was sufficient for phase conversion from α-BCC to γ-FCC (or α + γ) phase. It is the phase where all internal stresses are removed, and the grain structure of steel is recovered. The steel rods, then, are removed from furnace one by one for cooling up to room temperature. First rod was kept in atmospheric air. It took nearly 2.5 h to get cooled up to room temperature. Second sample was dipped in a small water tank. An approximate period of cooling this sample was 1 min. Third sample was inserted in 1 litre mustered oil. Oil provides a bit slower cooling rate than that of water. Therefore, the sample tool nearly 15 min to get cool down. The fourth sample was not taken outside the furnace. The power supply of the furnace was switched off and the chamber was closely packed so that air could not pass into it. In this condition, the sample got cooled nearly in 60 h. After 60 h also, the sample possessed enough heat that cannot be touched by hands. Hence, finally sample was cooled by water sprinkle. The induction furnace, heating process, cooling at different media and the heat-treated samples are shown in figure 2. As the heat-treated samples had rough appearance due to oxide layers, they were properly machined to make smooth surface. For this purpose, the samples were turned in lathe machine. The turning operations and the final smoothened heat-treated rods are shown in figure 2. Hence, based on cooling types, the samples can be named as Original sample (OS), Air-cooled (AC), Water quenched (WQ), Oil quenched (OQ), and Furnace cooled (FC).

2.3. Specimen preparation for tensile test and hardness test
For hardness test samples, a small portion (thickness 5 mm) of all the rods was cut from all the five specimens. These small samples were used for hardness test (on one side) and microstructural analysis (on another side).

The tensile test specimens were prepared from straight rods. For this, lathe machine was used to provide dog-bone shape as per ASTM standard. Test specimens were machined according to ASTM E8-16a in which
diameter of reduced section is 12.5 mm and gauge length is 50 mm. The radius of fillet parts was 10 mm. The prepared specimens are shown in figure 3. In image, numbers are written on samples. The meaning of these numbers is: 1- original sample; 2- air cooled sample; 3- water cooled sample; 4- oil cooled sample; 5- furnace cooled sample. The outer diameter of grip section of the specimens is 30 mm. Initially, it was assumed that 30 mm diameter rod could be fitted in the universal testing machine (UTM) but the jaw of UTM had a maximum limit of 15 mm only. Therefore, the outer diameter of the grip section was reduced to 15 mm, although image could not be captured by authors prior to test.

3. Tensile test and analysis

The tensile test was conducted in a servo hydraulic controlled UTM, named INSTRON 8800. This machine was utilised by the same author in another work [22]. The capacity of this UTM is 125 kN. A strain rate of 0.0015 s^{-1}
was kept for all the specimens. With an attached data acquisition system, load-extension graph begins to draw as soon as stretching starts. After performing all the tests, it was noticed that all the samples showed a similar kind of failure that is cup & cone fracture- obvious for a ductile material like low-carbon steel. The broken specimens and all the five graphs between load-extension are shown in figure 4. The measured values of ultimate tensile strength (UTS), maximum load, maximum extension and time taken to break the samples are also shown just below the graph of each condition (figure 4). The following points were mainly observed from tensile test results:

- The UTS of OS, AC, WQ, OQ, and FC samples are 532.07, 541.95, 545.47, 585.65, 418.43 MPa respectively. As compared to OS, all the heated treated product showed a good improvement in strength. It seems that UTS depends upon cooling rate. As soon as cooling rate is enhanced, UTS gets increased. There is an improvement of 1.8%, 2.4% and 10% in UTS of AC, WQ and OQ respectively as compared with OS. But a reduction in UTS was noticed in FC samples which is a significant value (21% lesser than OS).

- A reverse observation was noticed in the extension (till fracture) values. The samples which were cooled in slower rate showed high extension. High extension value is an indication of high ductility. The extension in OS, AC, WQ, OQ, and FC samples are 7.58, 7.68, 6.83, 7.01, 8.25 mm respectively. The highest elongation was noticed in FC means a good amount of ductility has been restored in the FC sample, as expected.

- A measurable difference in fracture load was also noted in all the samples. In OS, necking phenomenon was not lasted for longer time and the specimen failed at nearly 25 kN load. The AC sample failed at 16 kN load with a higher necking than that of OS. Water quenched specimen had failed at 20 kN and in this case also a higher reduction in area was noted than OS. OQ, despite being a fast-cooling process, showed a significant improvement in necking as the fracture load was 15 kN which is lesser than all above. Among all samples, FC sample had shown a fracture load of 8 kN which is a clear indication of high ductility as the largest elongation was reported in this sample.

4. Hardness test and analysis

As discussed above in methodology section, the cylindrical specimens of 5 mm thickness and 30 mm diameter were taken for hardness test (see figure 5). Rockwell hardness test was performed in each specimen. The test was generally done in two steps where firstly a minor load was applied followed by the major load. In doing so the difference between the penetration depth received from the minor load and the major load helped us to know about the hardness for the specimen. The test was conducted at a load value of 130 kgf with diamond indenter. Total 4 indents were made in each specimen and an average value of hardness was noted. Specimen-wise hardness (HRC) values and their comparison with each other are shown in figure 5. The OS had 73.67 HRC hardness whereas all the heat-treated samples showed a significant improvement in this. Air and furnace cooled samples possessed the same hardness that is 77 HRC. Furnace cooled sample was expected to show a lower value of hardness due to possessing high ductility. But, if both ductility and hardness are maintained in this, means
mechanical property has truly improved in the same. Water quenching has made the steel harder that OS, AC, and FC. WQ has enhanced the strength also. But the hardness of WQ is lesser than that of OC (103 HRC). Oil quenching has been proved again as superior that WQ. The microstructures will show the exact grain structure of all the samples.

Figure 6. Microstructural images after heat treatment (a) coarse pearlite and ferrite of original specimen (b) coarse pearlite and ferrite of air-cooled specimen (c) coarse pearlite and ferrite presence in water-quenched specimen (d) fine pearlite, ferrite, and martensite of oil-quenched specimen (e) furnace cooled specimen.
5. Microstructural analysis

The microstructure analysis into all the five samples were carried out in an optical microscope (make: Germany). Other sides of the hardness test specimens were utilized for this analysis. All the standard procedures like super-finishing process by using polishing machine and etchant preparation were carried out. Finishing was done up to mirror-like appearance. The etchant (Nital with 2.5% nitric acid) was applied properly at least 1 min before the observation.

The microstructural images are shown in figure 6(a)–(e) for all the samples- OS, AC, WQ, OQ, and FC. The microstructure mainly includes pearlite and pro-eutectoid ferrite. Pearlite, layered structure composing of alternating layers of ferrite and cementite (Fe₃C), was observed in the microstructure of all the five specimens along with ferrite. In the case of original specimen ferrite along with pearlite was observed with ferrite being present in majority. But in the case of air-cooled, water-quenched, oil-quenched and furnace cooled specimens, they showed an increase in the pearlite.

The appearance of pearlite was found changing as per cooling conditions. The original sample possessed a coarse pearlite whereas the water and oil quenched samples showed comparatively finer pearlites along with other needle like fine appearance.

The original specimen showed mainly coarse pearlite with pro-eutectoid ferrites, although the ferrite + cementite lamellar could not be seen in the specimen due to low magnification of microscope. As compared to original sample, air cooled sample showed a significant variation in the microstructure. We could see the fine micrographs with a dense pearlitic structure. The air provides a fast-cooling rate in which nucleation of pearlite started at multiple locations but could not grow due to achievement of room temperature soon. The structure of water-cooled specimen is completely different from original and air-cooled samples. Water quenched specimen mainly contained martensite with very less amount of very fine pearlite. The possibility of presence of retained
austenite could not be neglected in the water quenched sample as it has, probably, missed the transformation curve. Oil cooled sample, being rapidly cooled, has a completely different structure as compared to water quenched specimen. A mixture of bainite, fine pearlite and pro-eutectoid ferrite could be seen in the micrograph of the sample. In some places, there were formation of fine lamella of cementite and ferrite also. In furnace cooled sample, the microstructural appearance is again completely different from all other samples. The widely dispersed Ferrite regions were observed, mainly, in the sample. Apart from this, a less pearlite zone could also be reported in the study.

6. Fractographic analysis of tensile test specimens

All the broken tensile test specimens were undergone through fractographic analysis. In this, the fractured surface of the specimen was observed through field emission scanning electron microscopy (FESEM) to know
Table 2. Comparative analysis among mechanical properties.

| Sample           | Maximum Load [N] | Ultimate Tensile stress [MPa] | Comparative analysis | Tensile strain [mm/mm] | Comparative analysis | Hardness [HRC] | Comparative analysis |
|------------------|-------------------|-------------------------------|----------------------|------------------------|-----------------------|-----------------|----------------------|
| Original         | 35369.91          | 532.07                        | —                    | 0.166                  | —                     | 73.67           | —                   |
| Air-cooled       | 34784.67          | 541.95                        | 1.8%↑                | 0.168                  | 1.2%↑                 | 77              | 4.5%↑               |
| Water-quenched   | 35945.86          | 545.47                        | 2.4%↑                | 0.145                  | 13%↓                  | 97.67           | 32.5%↑              |
| Oil-quenched     | 39526.43          | 585.65                        | 10%↑                 | 0.159                  | 4.2%↓                 | 103             | 40%↑                |
| Furnace-cooled   | 27815.38          | 418.43                        | 21%↑                 | 0.190                  | 15%↑                  | 77              | 4.5%↑               |
the failure behaviour—Ductile or Brittle. The fractographic images of all the five samples are shown in figure 7. In original sample, a significant peak and valley formation, numerous micro–dimples, minor cracks are visible with an indication of ductile fracture. Also, one clearly visible cleavage facet could also be observed in the sample as a proof of brittle fracture. In air-cooled sample, there were multiple pores and dimples present but no facets and considerable peaks/valleys could be reported in the sample. It is due to grain size refinement due to heat treatment. The water quenched specimen had a clearly visible valley-like area. There were multiple small facets too. The water quenching makes the specimen hard and therefore the specimen acts nearly as a brittle material. The oil cooled specimen had nowhere facets means it overcame the limitations of water quenching. Also, several micro- and macro-dimples were the result of a detailed analysis. A minor peak—valley formation could also be observed in the sample.

7. Discussion

- The ultimate tensile strength values of Original, air-cooled, water cooled, oil cooled and furnace cooled sample were 532.07 MPa, 541.95 MPa, 545.47 MPa, 585.65 MPa, and 418.43 MPa respectively. As per our expectation, the heat treatment methods and cooling through air, water and oil have increased the tensile strength of the sample by 1.8%, 2.4%, and 10% respectively. Oil cooling method has provided the highest tensile in the sample. The furnace cooling approach has reduced the tensile strength of the sample by 21%. This is a significant reduction in strength but along with this a huge increment in elongation was recorded in the same sample. The strain value of the furnace cooled sample was found to increase by 15%. Similarly, air cooled sample has showed an increment in strain value by 1.2% (a small change). Water and Oil quenching have made the sample hard and therefore their ductile behaviour was affected. Their strain values were found to get reduced by 13% and 4.2% respectively. If we compare between Oil and Water quenched specimens, Oil cooled specimen had 7% higher ductility than water cooled specimen (See table 2).

- As per the hardness test results, all the heat treatment methods have improved the hardness of samples significantly. The highest hardness was achieved in Oil quenched specimen. Again, in hardness test also, Oil quenching has been proved as better approach that water quenching.

- The microstructures are in good corroboration with the mechanical properties. As the Original sample possessed coarse pearlite, its tensile strength and hardness are comparatively lesser than heat treated samples. The air cooling has made the microstructure slightly finer which results in an increment of strength and hardness. The water quenched specimen mainly contained martensite and very fine pearlite, the high strength and high hardness value along with less extension before fracture established the microstructural appearance. In contrary, Oil quenched sample possessed a combination of bainite, fine pearlite and some lamellar ferrite and cementite. Therefore, a good combination of strength, hardness and ductility was found in this sample. The furnace cooling has provided a sufficient time to nucleate the pearlite and let it grow throughout the ferrite regions. Therefore, the sample became too ductile, but the strength value has reduced significantly, However, hardness had no effect due to furnace cooling.

8. Conclusion

The present work deals with analysis of effect of heat treatment and continuous cooling transformation in Low-carbon steel samples. The effect was analysed on Two different mechanical properties like Tensile strength, and Hardness. Apart from this, the ductility of steel samples was also analysed based on extension values obtained from tensile test results. The Microstructural study was done to establish a corelation between mechanical properties and grain structure. The following conclusion can be made from this study:

- The tensile test results showed that heat treatment has positively improved the properties of steel samples. The tensile strength of original sample was 532 MPa. It was kept as standard based on which other heat-treated samples were compared. Air cooling and water quenching technique have improved the tensile strength by 1.8% and 2.4% respectively. A significant improvement in tensile strength (by 10%) was observed by Oil cooling method. Hence Oil cooling technique is better for strength enhancement. In contrary, furnace cooled sample has reduced the strength of the specimen, as expected, by 21%. Furnace cooling has provided a sufficient time to the sample to get converted into coarse pearlite which is a low-strength structure.

- From the tensile strain result it can be interpreted that there were ups and down in specimen when compared with the original one. The tensile strain for the original specimen was recorded 0.166 mm mm⁻¹. Keeping the original specimen as the base and comparing others with its value, it was observed that the oil-quenched and
water-quenched specimen had a decrease in tensile strain value by 4.2% and 13% respectively whereas the other two specimens, air-cooled and furnace-cooled specimen, had an increase in their tensile strain by 1.2% and 15% respectively. So, furnace-cooled specimen was able to bear the maximum tensile strain and water-quenched beard the minimum tensile strain.

- Oil-quenched specimen was able to bear the maximum load and furnace cooled had the minimum of them.

- As for the hardness, heat treatment had a positively improved the properties of the steel sample. Hardness for the original specimen was recorded 73.67HRC. This was kept as a standard and hardness for the other specimen were compared with the original one. It was noted that oil-quenched specimen had the maximum increase in hardness or about 40% followed by water-quenched specimen with an increase in hardness of about 32.5%. For the air-cooled and furnace-cooled specimen there was a same percentage increase in the hardness value of 4.5%.

- Pearlite and ferrite were observed in every specimen when viewed under microscope, and only in the case of oil-quenched specimen we, along with pearlite and ferrite, experienced formation of martensite. Martensite is a needle-shaped structures which forms when samples does not transform completely to pearlite. Original sample contained mainly coarse pearlite. Air cooling process has made the pearlite finer than that of original sample. Water quenching product has a completely different structure which includes Very fine pearlite along with martensite. There is a possibility of existence of retained austenite. Oil cooled sample showed a proper mixture of pearlite and martensite (or bainite).

- The mechanical properties of water-quenched, and oil-quenched sample are comparable, yet oil quenching is preferable over water quenching because it showed an increment of 7.6% in strength and 7.5% in hardness over the sample properties of water quenched product.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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