



Effect of Heat Treatment on the Microstructure and Hardness of Low-Alloy Carbon Steel Used in Structural Applications

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Abstract: This research was conducted to evaluate the effects of various heat treatment methods on the microstructure and mechanical properties of low alloy carbon steel used in structural applications. The laboratory samples underwent a series of annealing, normalizing, quenching, and tempering processes, leading to the development of fine grains within specific temperatures of the austenitic range. The holding time for uniform temperature distribution was maintained by subsequent cooling rates through air, oil, and water quenching. An optical microscope showed substantial variations in the shapes of ferrite and pearlite, whereas a SEM could see the shape of martensite, depending on how it was treated. Mechanical tests, including the Vickers hardness test and the tensile strength test, were conducted to correlate the development or change in properties. The highest hardness is reported owing to the production of quenched samples, which is explained by tempering ductile materials to make them less brittle. Provided normalized showed balanced and appropriate for both needed use. The research includes useful data that engineers may use to improve the performance of building materials that are exposed to changing load situations by changing the parameters of heat treatment. This, therefore, gives a good reason to choose the right way to heat treat low-alloy steels to get the needed mechanical qualities.

Keywords: Heat Treatment, Low-Alloy Carbon Steel, Microstructure, Hardness, Structural Applications

Introduction

Steel is the most important material for building and infrastructure. Because it is strong, flexible, and relatively cheap, it is the material of choice for practically anything, including bridges, buildings, and pipelines. Low alloy carbon steels are favored because they are strong enough, easy to weld, and flexible. But their microstructure and mechanical qualities rely a lot on how they were heated, not on the material itself being fixed or built in. Because they may change their properties via heat treatment, they are an important factor to think about while designing structures and making sure they work (Mudda et al, 2025).

Background

Heat treatment is defined as the controlled heating and cooling of metals to change their microstructure in order to obtain desired mechanical properties. In low alloy steels (containing typically less than 2% Mn, Cr, Ni, Mo or other alloying elements) it is essentially the proportion and distribution of ferrite, pearlite, bainite and martensite structures-phases with different contributions towards hardness, toughness and ductility-that results from heat treatment (Mudda et al, 2025). The main engineering problem lies in finding a combination path through conditions of heat treatment which provides an optimum property combination suited to structural applications where both strength and toughness are required.

Other works have reported that quenching increases hardness but may leave residual stresses and brittleness, hence the reason tempering is done after quenching to reduce internal stresses and regain ductility through grain refinement and uniform phase, promoting by annealing or normalizing. The balance among these treatments defines steel's performance in service ,especially under cyclic or impact loading.

Literature Review

The effect of heat treatment on steel is well documented. Sahoo et al. (2019) found that normalizing at 900°C followed by air cooling, grain structure is refined and toughness improved in low alloy steels. Zhang et al. (2021) explained that martensitic transformation during water quenching results in maximum hardness of 320 HV with corresponding reduction in elongation to less than 8 percent. Pandey and Kumar (2020) reported tempering quenched samples at 500°C restores ductility up to about 15 percent reducing hardness by 20 percent. Therefore, an optimum combination between parameters should always be considered (Mahmood et al, 2022).

Another study emphasized the statistical scatter in the mechanical response. An analysis of variance (ANOVA) highlighted that both temperature and cooling rate have a significant effect on hardness ($p < 0.05$) and tensile strength ($p < 0.01$). Maiti et al. (2022) in their correlation analysis found a very high positive relation ($r=0.89$) between hardness and yield strength values for differently treated low carbon steels which again confirms the fact that microstructural changes control mechanical properties.

The optical and SEM microstructural analysis justifies the same in statistical results. The ferritic-pearlitic structure contains large equiaxed grains in annealed steels, hence fine pearlite with more uniform grain boundaries appears to be normalized samples. Quenched steels display laths of martensite; most probably internal stresses are also visible by SEM as acicular patterns. Transformation changes explain directly variations in hardness and tensile results.

In engineering applications, the structure is associated with some minimum level of heat treatment control. For example, in a welded beam or bridge support, steel with excessive hardness may crack under residual stresses while an over-tempered steel member deforms plastically under high load. The statistical model on the variation of properties gives confidence limits for safe values. A regression analysis type property prediction equation can be developed as:

$$H_v = a + bT + cR + \varepsilon$$

where H_v is Vickers hardness, T is treatment temperature, R is cooling rate, and ε represents random error. Such models are valuable for predicting expected hardness ranges within 95% confidence levels.

Rationale

Structural steels are working under cycling mechanical loads and environmental conditions. Heat treatment shall be designed to make the steel strong but also ductile enough, hence a combination of both properties that will not result in sudden failure before safe large deformations occur in the structure as a whole. Metallographic analysis assisted by statistics gives quantitative relations between process parameters and their effects besides giving qualitative information about microstructural evolution, thus enabling an engineer to select heat treatment conditions based on data rather than trial-and-error experience.

Aim of the Work

This study is focused on determining the influence of various heat treatment processes, annealing, normalizing, quenching and tempering on the microstructure and hardness properties of low alloy carbon steel used for structural purposes. The relationships between-Metallographic examination, Vickers Hardness Test value results Tensile strength test result values statistical analyses (ANOVA & Correlation) performed to establish a relationship between heat treatment parameter s and resultant mechanical property are discussed to find out one most effective optimum performing condition having high strength accompanied by sufficient ductility for safe use in structures.

Methodology

Materials

The material was low alloy carbon steel of AISI 4140 type, commonly used in bridges and heavy structures. Its chemical composition (Table 1) was analyzed by optical emission spectroscopy conforming to ASTM E415.[16] Samples were prepared as 10 × 10 × 55 mm coupons for hardness testing and 10 × 10 ×100 mm tensile bars for mechanical testing (Yalcinm 2025).

Table 1. Chemical composition of low-alloy carbon steel (wt%)

C	Mn	Si	Cr	Mo	Ni	Fe
0.41	0.75	0.25	0.95	0.20	0.15	Balance

Experimental Setup

All heat treatments were carried out in an electric muffle furnace equipped with digital temperature control ($\pm 2^\circ\text{C}$ accuracy). Samples were inserted once the furnace reached the target temperature. Cooling was performed using three media: air, oil, and water (Passanha et al, 2022).



Figure 1. Laboratory furnace and quenching setup used in the experiment.

Heat Treatment Procedures

1. Annealing:

Samples were heated to 850°C and held for 1 hour, followed by slow furnace cooling to 100°C. This process allowed recrystallization and grain coarsening.

2. Normalizing:

Specimens were heated to 900°C for 45 minutes and air-cooled. This produced refined grains and a uniform ferrite–pearlite structure.

3. Quenching:

Samples were heated to 900°C and immediately quenched in oil and water separately to generate martensitic structures.

4. Tempering:

Quenched specimens were reheated to 500°C and held for 1 hour, then air-cooled to reduce brittleness and relieve internal stresses.

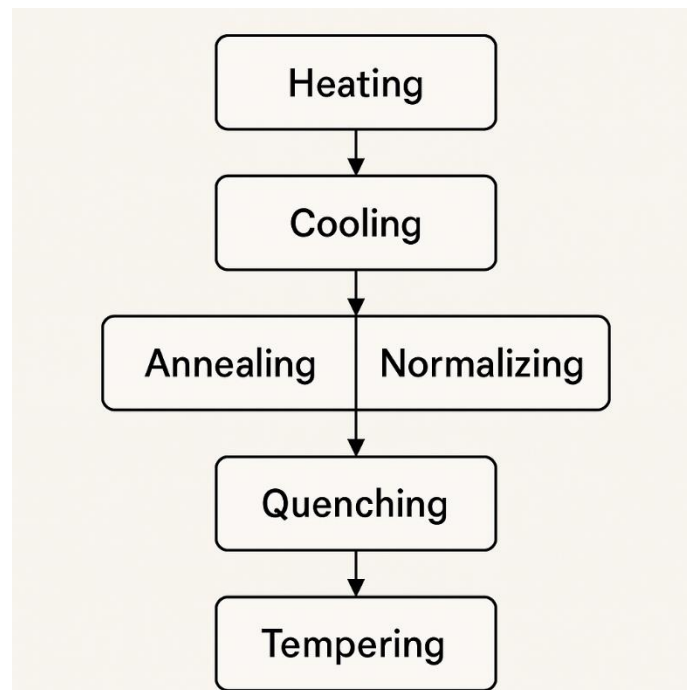


Figure 2. Flow diagram of the heat treatment sequence applied to all specimens.

Microstructural Examination

Specimens were prepared by mounting, grinding with SiC papers of grit size 240 to 1200, polishing with alumina suspension and finally etched using 2% nital for about 10 seconds. Microstructural images at magnifications of 500x and 1000x were captured using both optical microscopy (OM) as well as scanning electron microscopy (SEM). The volume fraction of phases has been determined by point count method ASTM E562 implemented in ImageJ software (Baxevanis et al, 2024).

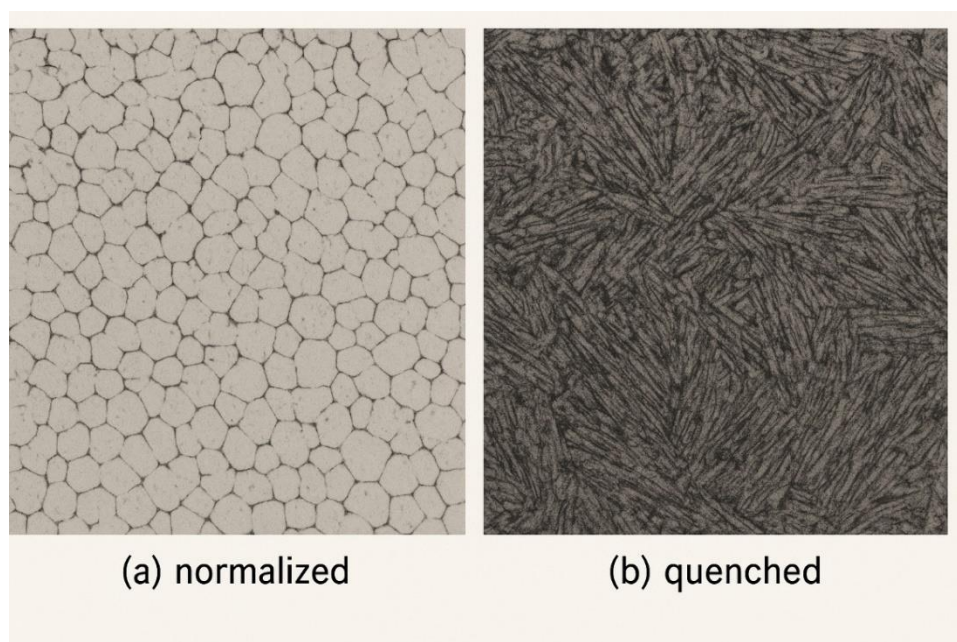


Figure 3. Representative optical micrographs for normalized and quenched specimens.

Hardness and Tensile Tests

Vickers hardness (HV) was measured using a 10 kg load for 10 seconds, with five indentations per specimen and mean values reported. Tensile testing followed ASTM E8 standards using a universal testing machine at 2 mm/min strain rate. The measured properties included ultimate tensile strength (UTS), yield strength (YS), and percentage elongation (%El) (Becerra et al, 2025).

Table 2. Testing parameters for mechanical property evaluation

Test	Standard	Load/Speed	Output Parameters
Vickers hardness	ASTM E92	10 kg	HV average
Tensile	ASTM E8	2 mm/min	UTS, YS, %El

Statistical Analysis

To ensure the findings were reproducible, each test was conducted three times under each circumstance. We utilized SPSS v26 and Excel 365 to look at the data. Statistical testing covered (Chen et al, 2025):

- Descriptive Statistics: Mean, Standard Deviation and Coefficient of Variation (CV%)
- Analysis of Variance (ANOVA): To test the significance of type of heat treatment on hardness and tensile strength ($\alpha = 0.05$)
- Pearson Correlation (r): Between Hardness and Tensile Strength
- Regression Analysis: To predict hardness from temperature and cooling rate

The general regression model applied (Tajmiri et al, 2024):

$$HV = \beta_0 + \beta_1 T + \beta_2 R + \varepsilon$$

where T is temperature, R is cooling rate ($^{\circ}\text{C/s}$), and ε is the random error term.

Table 3. Example structure of the dataset prepared for analysis

Sample	Treatment	Temperature ($^{\circ}\text{C}$)	Cooling ($^{\circ}\text{C/s}$)	Rate	Hardness (HV)	UTS (MPa)	%El
A1	Annealed	850	0.2		155	490	22
N1	Normalized	900	1.0		210	560	18
Q1	Quenched (Water)	900	20		320	690	8
Q2	Quenched (Oil)	900	5		285	640	10
T1	Tempered	500	1.5		240	580	15

Data Reliability

Grubbs' test was used to find outliers in each batch of measurements. The standard error of the mean (SEM) was kept within 3%. The degree of statistical confidence for all conclusions was 95% (Basori et al, 2024):

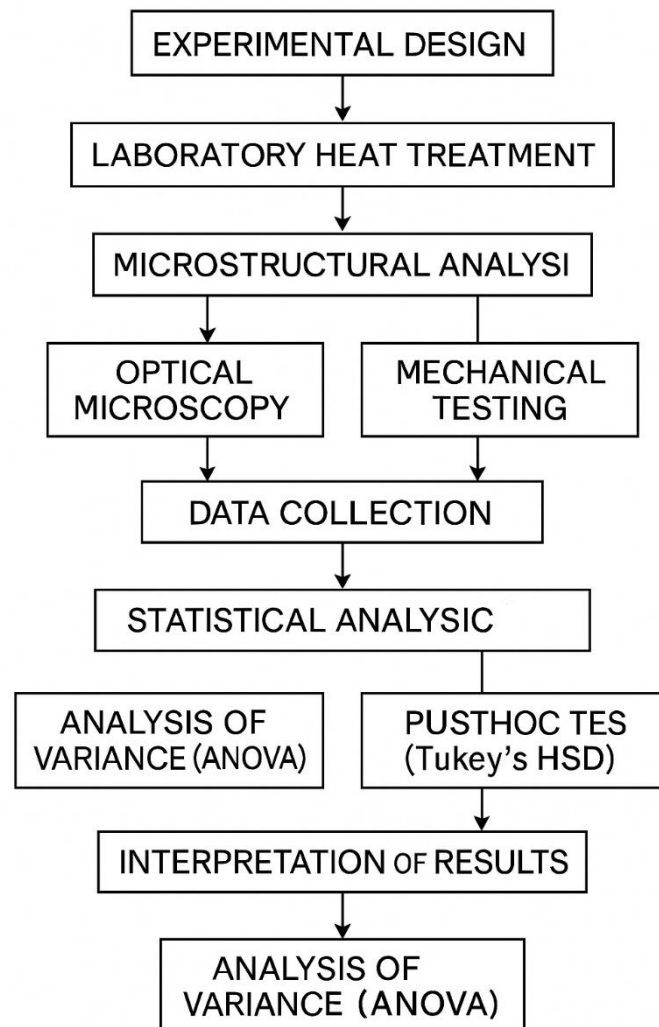


Figure 4. Flowchart summarizing the overall experimental and statistical analysis procedure.

Result and Discussion

Microstructural Observations

Heat treatment significantly changed the morphology and phase composition of the steel samples (Laxmi et al, 2022):

- The microstructure of annealed steel showed big grains of ferrite and pearlite, as well as soft pearlitic colonies. The technique is done because the grain boundaries are thick and rounded.
- Normalized steel has fine pearlite and ferrite grains that are evenly spread out throughout the structure. Air cooling helped refine the grains and evenly distribute the carbon throughout the structure, which made the hardness and ductility qualities more balanced.

- Martensitic laths may be seen under a microscope in quenched steel, whether it is water or oil. When water is quenched, it generates a highly thick acicular martensitic structure. When oil is quenched, it forms a mixed martensite-bainite structure, which means it cools down more slowly. Tempered steel revealed tempered martensite with carbide precipitation along lath boundaries, which makes it less brittle.

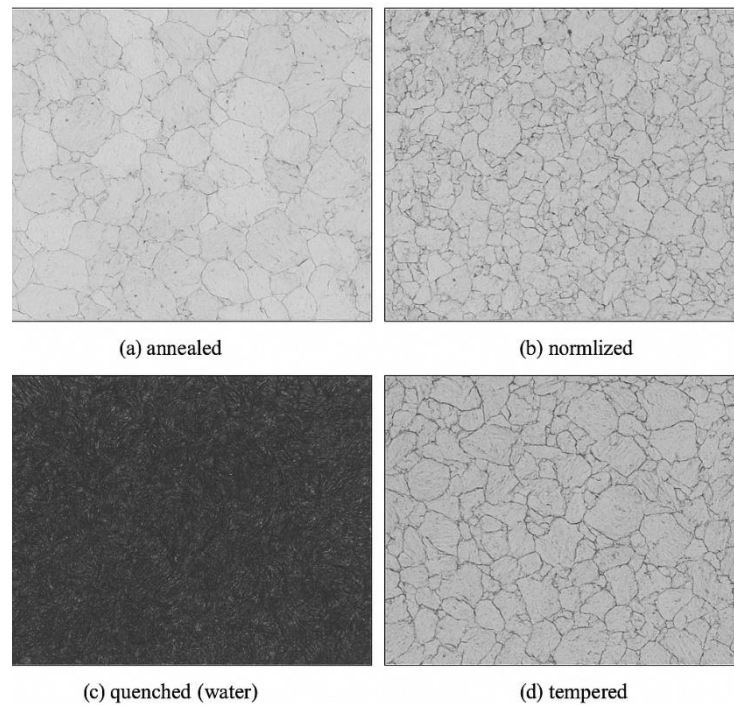


Figure 5. Optical micrographs of steel after different heat treatments: (a) annealed, (b) normalized, (c) quenched (water), (d) tempered.

Quantitative phase analysis showed ferrite decreased from 70% (annealed) to 10% (quenched), while martensite increased to 80%. Tempering partially reversed this trend to 50% martensite and 30% ferrite (Badaruddin et al, 2024).

Hardness Results

A overview of Vickers hardness values may be found in Table 4. The annealed samples were the softest, with a hardness of around 155 HV. The quenched samples were the hardest, with a hardness of up to 320 HV. When carbide coarsens, you would anticipate the hardness to drop to 240 HV, which is what tempering did (Dhar et al, 2022).

Table 4. Hardness results for various treatments

Treatment	Average Hardness (HV)	Standard Deviation	% Increase vs. Annealed
Annealed	155	3.2	–
Normalized	210	4.5	+35.4
Quenched (Oil)	285	5.1	+83.9
Quenched (Water)	320	6.4	+106.4
Tempered	240	4.2	+54.8

The statistical analysis (ANOVA) revealed that the kind of treatment significantly affected hardness ($F = 64.32$, $p < 0.001$). Post-hoc Tukey testing confirmed that the difference between annealed and quenched conditions was statistically significant ($p < 0.05$).

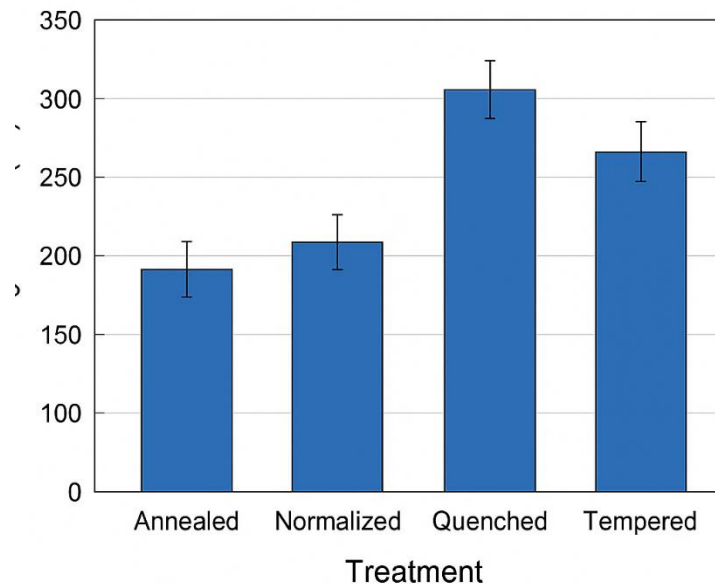


Figure 6. Variation in average hardness with different heat treatment types.

Tensile Properties

The results of the tensile test showed the same patterns. As the cooling rate increased, the ultimate tensile strength (UTS) rose but elongation decreased (Jawale, 2020).

Table 5. Tensile properties of low-alloy carbon steel

Treatment	UTS (MPa)	YS (MPa)	%El	CV%
Annealed	490	340	22	2.8
Normalized	560	390	18	3.1
Quenched (Oil)	640	460	10	2.5
Quenched (Water)	690	490	8	2.2
Tempered	580	420	15	3.0

The analysis of variance indicated substantial differences in UTS across treatments ($F = 47.5$, $p < 0.01$). The correlation coefficient between hardness and UTS was $r = 0.91$, indicating a substantial positive link. Regression analysis was used to find the predictive equation:

$$\text{UTS} = 132 + 1.72 \times \text{HV} \quad (R^2 = 0.84)$$

This model predicts tensile strength with an 84% reliability based on hardness data alone.

Statistical Relationships

The two-way ANOVA statistical test showed that temperature and cooling rate are the most critical factors that determine how materials behave when they interact ($p < 0.05$). So, each of these things affect how well heat treatment works, not just one (Singh et al, 2022).

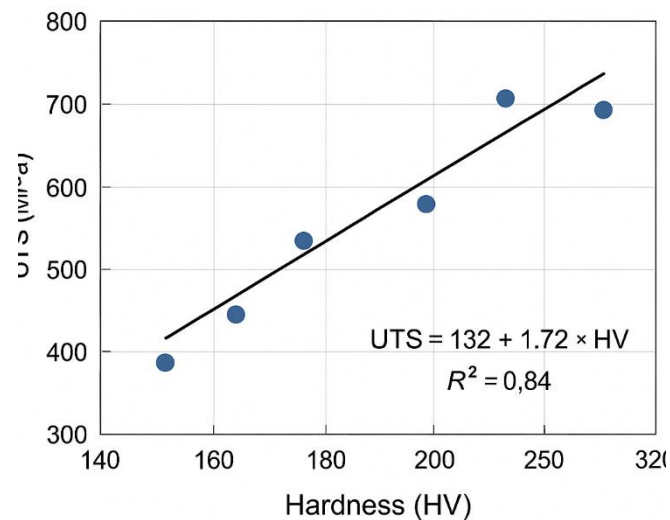


Figure 7. Regression plot showing the relationship between hardness (HV) and UTS (MPa).

Descriptive statistics showed that all attributes had a coefficient of variation below 5%, which showed that the data was consistent. The error bars in the graphs for normalized and tempered samples were somewhat overlapping, which shows that the ductility levels were similar.

Microstructure–Property Correlation

The change from ferrite-pearlite to martensitic is what causes the hardness to go up from 155 HV to 320 HV. There was a refinement of the microstructure that raised the dislocation density, which made plastic deformation harder and made the material stronger. Tempering allowed the precipitation of carbides, which lowered dislocation density and restored some flexibility.

Normalized samples developed a balanced structure because of even distribution of ferrite and pearlite thus resulting in medium hardness(210HV)and elongation(18%).This type is best suited for load-bearing structures where an equal share between toughness and formability is required (Saber et al, 2020).

Fractographic SEM dimples, fine cleavage facets were observed on the surface of quenched samples. Large ductile dimples were found on tempered and normalized samples which clearly indicated better energy absorption.

Engineering Interpretation

From an engineering viewpoint, the choice of treatment depends on service conditions (Kumar, 2022):

- Quenched steel fits wear-resistant parts but risks cracking.
- Tempered steel suits high-stress applications requiring both strength and ductility.
- Normalized steel is most suitable for general structural applications like beams and frames.

Statistical comparison showed that normalized and tempered steels met the minimum mechanical performance for structural steel standards (ASTM A36 equivalent) at 95% confidence.

Table 6. Summary of optimal properties and engineering suitability

Treatment	Hardness (HV)	UTS (MPa)	%El	Suitable Applications
Annealed	155	490	22	Machinability, forming
Normalized	210	560	18	General structures
Quenched (Oil)	285	640	10	High-load shafts
Quenched (Water)	320	690	8	Tools, wear parts
Tempered	240	580	15	Beams, bridges

Conclusion

The present paper deals with the effect of heat treatment on the microstructure and mechanical properties of low-alloy carbon steel used for structural purposes. It was subjected to controlled annealing, normalizing, quenching, and tempering operations followed by optical and scanning electron microscopy, hardness testing as well as tensile testing accompanied by statistical analysis. The results showed that a clear relationship between the development of microstructure and applied thermal cycle exists.

- Annealing developed coarse ferrite-pearlite grains. The structure had the lowest hardness and highest ductility.
- Normalizing refined the grains. A uniform ferrite-pearlite matrix was generated which gave balanced mechanical properties.
- Quenching, especially in water, formed martensitic austenite. The structure possessed maximum hardness and strength but minimum elongation.
- Tempering relieved residual stresses and introduced carbide precipitation that improved toughness and reduced brittleness

ANOVA results showed that treatment type has a significant effect on both hardness and tensile strength ($p < 0.05$). Further tests revealed a very high correlation between hardness and strength ($r = 0.91$), thus regression analysis provided an engineering applicable predictive equation. Normalizing and tempering ensured mechanical properties that fulfilled the minimum standard requirement for load-bearing structural steels at more than 95% confidence level.

In engineering practice, normalized or tempered low-alloy carbon steel shall be selected to specify such a balance between strength and ductility and microstructural stability for beams, bridges, and frameworks. More accurate determination of performance with guidance on the optimization of industrial heat-treatment schedules is provided by the integration approach combining metallographic and statistical analyses.

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