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# Investigating the impact of heat treatment on mechanical behaviour of A36 low-carbon steel

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## Abstract

Quenching and tempering processes are commonly employed to enhance the physical and mechanical properties of multiphase steels. This study investigated the effects of heat treatment on ASTM A36 low-carbon steel, a material well-suited for structural applications. The novelty of this study lies in the detailed investigation of the quenching and tempering processes applied to ASTM A36 low-carbon steel, focusing on specific tempering temperatures and varying soaking times. The specimens were heated to 900°C and soaked for 2 hours, followed by quenching in an oil bath. Subsequently, they were tempered at low (200°C), medium (300°C), and high (400°C) temperatures for 60, 90, and 120 minutes, respectively. The mechanical properties of the processed specimens, including hardness, tensile strength, and impact strength, were evaluated. The Rockwell hardness showed a significant improvement of 22.75% after treatment. Oil bath quenching followed by tempering increased the ultimate tensile strength by 31.51% and 29.36%, respectively, compared to steel without any heat treatment. However, elongation at break and impact strength decreased by 11.55% and 27.27%, respectively, during quenching. Low, medium, and high temperature tempering at various soaking times released the internal stresses, refined the grain structure and exhibited the effect on tensile strength, as well as improved the elongation at break and impact strength by 35.08% and 125%, respectively, compared to quenched steel.

**Keywords:** Heat treatment; Quenching; Tempering; Tensile strength; Low-carbon steel; A36

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## 1. Introduction

Steel is one of the most critical materials in modern industry, essential in construction, automotive, manufacturing, and infrastructure applications due to its versatility and strength. The heat treatment of low-carbon steel plays a vital role in optimising its mechanical properties for various industrial uses. Low-carbon steel A36, with a carbon content of up to 0.3%, is widely used due to its balanced combination of strength, ductility, and cost-effectiveness [1−3]. However, untreated low-carbon steel often lacks the hardness and wear resistance required for demanding applications. Heat treatment processes such as quenching, normalising, annealing and tempering are applied to alter the microstructure of the steel, significantly enhancing its strength, hardness and durability. By controlling parameters such as temperature and cooling rate during these treatments, the material properties can be customised to meet specific requirements [4,5].

The heat-treatment process is a combination of operations involving the heating and cooling of metals in different media such as water, oil, atmosphere, and brine solutions. It softens the metal, refines grain size, improves strength, and relieves internal stress [6]. The duration of heating at a particular temperature and the rate of cooling in different media play an essential role in achieving the desired mechanical properties of any steel [7].

## Nomenclature

**Greek symbols**
Ø – diameter, mm

**Abbreviations and Acronyms**
ASTM – American Society for Testing and Materials
HTT – high temperature tempering
LTT – low temperature tempering
MTT – medium temperature tempering
QCH – quenching
UTS – ultimate tensile strength
WHT – without heat treatment
YS – yield strength

Multi-step heat treatment can enhance the toughness of low-carbon, precipitation-strengthened steel with minimal reduction in yield strength. The high strength of steel is achieved by carefully creating internal barriers that hinder dislocation movement [8,9]. The improvement in toughness is partially attributed to reduced copper (Cu) segregation. However, tempered martensite may exhibit a slight decrease in strength due to a reduction in dislocation density, coarsening of precipitates, and a decrease in solute content [10−14]. Heat treatment of bimetallic additively manufactured structures (BAMS) at elevated temperatures and specific durations significantly improved ultimate tensile strength and elongation compared to untreated BAMS [15]. As a result of heat treatment, the failure shifted from the low-carbon steel side to the stainless-steel side [16,17].

The heat treatment process is an effective method for alleviating post-weld effects. Numerous studies have examined the impact of heating temperature, cooling medium temperature, heating rates, duration and cooling rate. Findings show that soaking temperature plays a major role in reducing residual stresses, while heating rate has minimal effect [18−20]. The addition of the niob (Nb) element improves the tensile strength and elongation of break of the weld metal without the need for heat treatment after welding, while having no impact on toughness. The Nb-free weld metal's strength was reduced by stress relief annealing; however, its elongation and impact toughness were improved [21]. The duration of austenitization significantly influenced the austenitic grain size, resulting in enhanced toughness of the alloy [22].

Nagar et al. [23,24] explored the critical role of heat-treatment in enhancing the durability and performance of manganese steel cone crusher liners. Rawat et al. [25] also investigated the effects of heat treatment on the microstructure and mechanical behaviour of A356/SiC metal matrix composites (MMCs), specifically focusing on tensile properties, hardness, and impact behaviour. They reported that adopting the heat-treatment processes reduced internal stresses in the metal matrix, contributing to improved mechanical performance. Li et al. [26] studied the cryogenic treatment of low-carbon steel and observed that applying cryogenic treatment combined with quenching and tempering to low-carbon martensitic stainless bearing steel enhances its mechanical properties by increasing hardness and tensile strength [27]. Cryogenic treatment reduces retained austenite, though some remains despite high-temperature tempering. Repeated cryogenic and tempering cycles further refine the martensite laths, leading to improved strength and wear resistance, but also result in a slight reduction in toughness [28,29]. These findings indicate that a well-optimised sequence of cryogenic and heat treatments can significantly enhance the durability and stability of this steel type for demanding applications [30]. The retention of austenite is enabled by austenitization, followed by quenching and partitioning, whereas carbon partitioning from martensite to austenite has a limited role in the creation of multiphase low-carbon steel [31,32].

Aminah et al. [33] examined how cryorolling, a low-temperature processing method, affects low-carbon steel with varying pre-annealing temperatures. The optimal results were achieved with pre-annealing at 550°C and 50% thickness reduction, leading to the highest grain aspect ratio (4.19), smallest crystallite size (28.8 nm), maximum microhardness (162.3 HV) and tensile strength (567 MPa). These enhancements were due to nano/micro-scale ferrite grains, dispersed $Fe_3C$ particles, and increased dislocation density. Other research [34,35] highlights cryorolling as a simple, efficient method for producing ultrafine-grained materials, with initial grain size playing a key role in final properties. Similarly, Kumar et al. [36] focused on the fabrication and analysis of zinc sulfide (ZnS) thin films deposited on glass substrates using the spin-coating technique at a high temperature of 500°C. They observed that post-deposition heat treatment process and precise control of film thickness played a crucial role in achieving desired material performance by improving the crystalline structure of the ZnS films.

Literature studies show the importance of heat treatment, which plays a vital role in achieving the desired mechanical properties of low-carbon steel. This study lies in its detailed investigation of the quenching and tempering processes applied to ASTM (American Society for Testing and Materials) A36 low-carbon steel, focusing on specific tempering temperatures (200°C, 300°C and 400°C) and varying soaking times (60, 90 and 120 min). A comprehensive evaluation of mechanical properties, such as hardness, tensile strength, elongation at break, and impact strength, demonstrates the systematic influence of these parameters on the steel's performance.

## 2. Experimental study

An experimental investigation was conducted on low-carbon steel ASTM A36 following heat treatment. Mechanical tests were performed to evaluate changes in tensile strength, hardness, and impact strength of the heat-treated samples. ASTM A36 was selected because of its suitability for structural applications. Table 1 shows the chemical composition of ASTM A36 low-carbon steel derived from spectrographic analysis.

Table 1. Composition of ASTM A36 by wt.%.

| C | Mn | Cu | P | Si | S | Fe |
|---|---|---|---|---|---|---|
| **0.25** | 1.03 | 0.2 | 0.04 | 0.28 | 0.05 | 98 |

## 2.1. Preparation of specimen

For the specimen preparation of low-carbon steel A36, a 10 m long steel rod of diameter 12 mm was considered along with a 10 mm × 10 mm bar. The three sets of dimensions: set I (15 × Ø 12 mm), set II (100 × Ø 12 mm), and set III (55×10×10 mm) were utilised for hardness, tensile, and Charpy impact tests, respectively. Three replicates of each sample were prepared for each experiment and tested. The average result has been presented for the accuracy of the results. For the specimen preparation, the ASTM E10, ASTM E8, and ASTM E32 standards were followed for the hardness, tensile strength, and impact strength tests, respectively. The dimensions and prepared specimens are shown in Figs. 1 and 2, respectively. The specimens were precisely machined using a BatliBoi 16TC CNC lathe and a vertical milling machine to achieve the required dimensional accuracy. This machining process ensured uniformity in specimen geometry and minimised stress concentration, thereby improving the reliability of the mechanical test results.

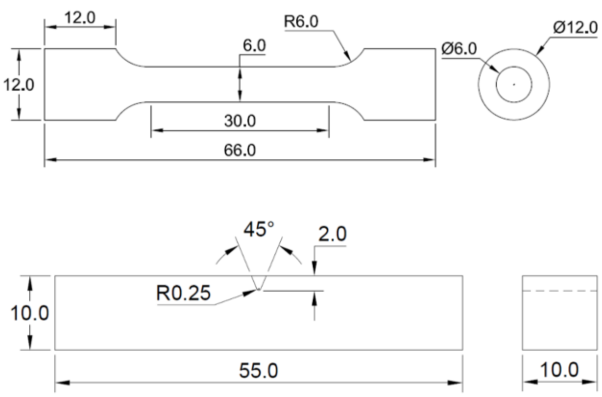


Fig. 1. Dimensions of tensile and impact strength test specimen [37,38].


Fig. 2. Prepared test specimens based on ASTM standards.

## 2.2. Heat treatment of the specimen

For heating the specimens, a muffle furnace was utilised. The specimens were heated inside the furnace above the critical temperature, i.e., 900°C for 2 hours. In this study, samples underwent quenching at 900°C using both oil and water as quenching media. The heated specimens were left to cool for 30 min in both quenching media. Quenching is a critical process that helps to improve steel's hardness, strength, and wear resistance. The taken-out, cooled and cleaned specimens were dipped into fresh water at ambient temperature for 10 min. The process of heating and cooling is shown in Fig. 3.

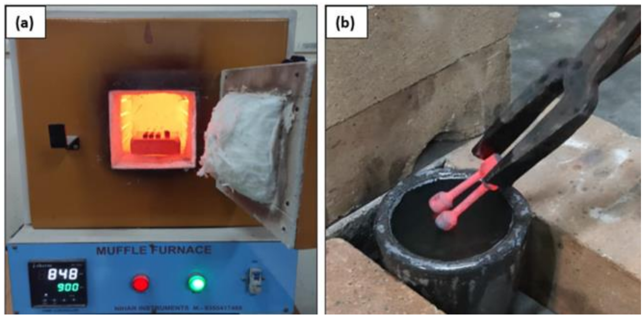


Fig. 3. Heat treatment process: (a) heating in a furnace, (b) quenching.

Following the quenching process, tempering was performed to reduce brittleness and relieve internal stresses in the specimens. This involved reheating the specimens below the recrystallisation temperature. During the tempering process, the specimens were heated to temperatures of 200°C (low), 300°C (medium) and 400°C (high). The tempering process was conducted for 60, 90, and 120 minutes. After completing the process, the specimens were left to cool in the air at room temperature.

## 3. Mechanical characterisation

The analysis of the mechanical properties of low-carbon steel A36 was performed. The Rockwell hardness, tensile, and impact strengths were tested with and without heat-treated specimens.

### 3.1. Hardness testing

The Rockwell hardness of the A36 low-carbon steel was measured using a hardness tester following the ASTM E10 standard. A diamond indenter with a 120° cone angle was used on the C scale. First, a minor load of 10 kgf was applied to remove any surface irregularities. Then, a major load of 150 kgf was applied through the indenter. The indentation depth was recorded from the dial gauge as arbitrary hardness numbers, which were then converted to standard hardness values using a conversion chart.

### 3.2. Tensile strength testing

Tensile strength testing was conducted on ASTM E8 standard specimens, using an electronic tensometer (PC-2000, KIPL) equipped with a 20 kN load cell and operating at room temperature, shown in Fig. 4. The tests were conducted at the Noida Institute of Engineering and Technology (NIET), Greater Noida. The ultimate tensile strength (UTS), yield strength (YS), and percentage elongation were measured. A round specimen with a gauge length of 30 mm and a gauge diameter of 6 mm was used. The test was performed at a constant strain rate of 1 mm/s,

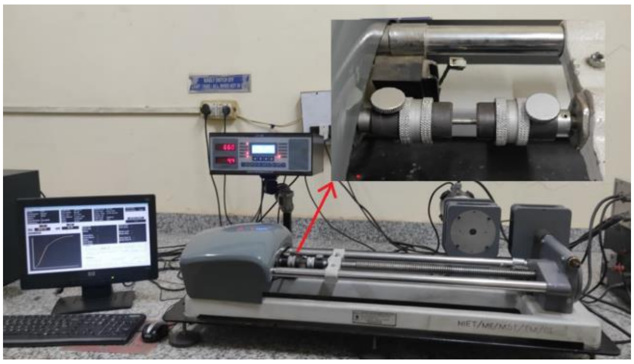

Fig. 4. Tensile strength test instrument, tensometer.

recording load vs. displacement and stress vs. strain plots. UTS, YS, and percentage elongation were calculated from the recorded data.

### 3.3. Impact strength testing

The impact strength of the specimens was measured using the Charpy impact test, following ASTM E23 standards. This test measures the impact energy or toughness of the specimens by quantifying the energy absorbed before fracture.

## 4. Results and discussion

The Rockwell hardness, tensile strength, and impact strength tests were conducted on standard specimens to evaluate the effect of the heat-treatment process.

Primarily, in the present study, samples underwent quenching at 900°C using both oil and water as quenching media. The results indicate that water quenching significantly reduces the material's tensile strength, elongation, and impact energy absorption by 5.83%, 10.24%, and 14.28%, respectively, compared to oil quenching of A36 low-carbon steel. This decline in tensile strength, ductility and impact strength is attributed to the rapid cooling rate, which promotes the formation of brittle martensite, a phase that absorbs less energy before fracturing. However, hardness increased by 8.06% from 95.5 HRC to 103.2 HRC due to martensitic transformation, which enhances the material's resistance to deformation. Both oil and water quenching significantly impact material properties. While water quenching results in higher hardness but greater brittleness, oil quenching offers a more balanced approach, reducing the risk of cracking and distortion. Water quenching has the most significant effect on material properties due to its rapid cooling rate, which drastically alters hardness and microstructure. However, for applications requiring a combination of strength and dimensional stability, oil quenching is often preferred.

### 4.1. Rockwell hardness

The Rockwell hardness test results of the specimens are shown in Table 2, comparing conditions without heat treatment, after quenching, and at different tempering temperatures and soaking times. Three samples were tested for each condition, and the mean hardness value was calculated from the three trials.

The variation in hardness due to quenching and tempering the A36 steel at different conditions is shown in Figs. 5−7. It is observed that the Rockwell hardness of the quenched sample (B) is 22.7% higher than that of the sample without heat-treatment (A). The variation due to different tempering temperatures and soaking times was also studied. The variation due to tempering temperatures, viz. low (200°C), medium (300°C) and high (400°C), along with soaking times of 60, 90, and 120 min among the samples, is not significant. Overall, the hardness of the A36 material increases due to the heat treatment process. It is due to the steel structure changing into austenite with a considerable amount of cementite. The rapid rate of cooling changes developed austenite into martensite. Due to structural changes in the steel, the hardness of the A36 improved. The quenching of steel improved its hardness and improved strength of steel. It has also been noticed that tempering and soaking time decreased the quenched samples' hardness.

The effect of tempering temperature and the soaking time has also been analysed and shown in Fig. 8. It has been found

Table 2. Rockwell hardness of A36 low-carbon steel.

| Sample ID | Heat treatment process# | Heating condition (°C/min) | Rockwell hardness (HRC) | | | Mean hardness (HRC) |
|---|---|---|---|---|---|---|
| | | | Trial 1 | Trial 2 | Trial 3 | |
| A | WHT | – | 76.2 | 78.5 | 78.8 | 77.8 |
| B | QCH | 900 / 120 | 97.2 | 95.4 | 93.8 | 95.5 |
| C | LTT | 200 / 60 | 87.9 | 86.3 | 88.1 | 87.4 |
| D | LTT | 200 / 90 | 86.8 | 85.5 | 89.0 | 87.1 |
| E | LTT | 200 / 120 | 86.9 | 85.9 | 86.2 | 86.3 |
| F | MTT | 300 / 60 | 83.9 | 81.8 | 82.9 | 82.9 |
| G | MTT | 300 / 90 | 85.2 | 80.2 | 82.8 | 82.7 |
| H | MTT | 300 / 120 | 79.3 | 82.6 | 83.8 | 81.9 |
| I | HTT | 400 / 60 | 77.5 | 81.2 | 76.3 | 78.3 |
| J | HTT | 400 / 90 | 76.6 | 79.4 | 78.4 | 78.1 |
| K | HTT | 400 / 120 | 79.6 | 77.7 | 76.3 | 77.9 |

#WHT – without heat treatment, QCH – quenching, LTT – low temperature tempering, MTT – medium temperature tempering, HTT – high temperature tempering.

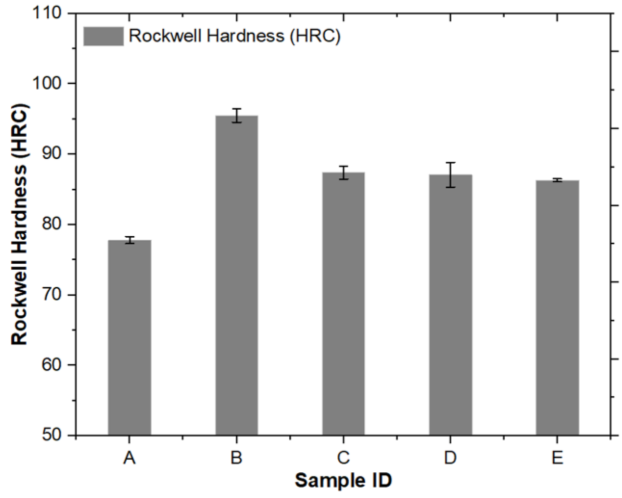


Fig. 5. Effect on the Rockwell hardness for WHT (A), QCH (B) and LTT (C, D and E).

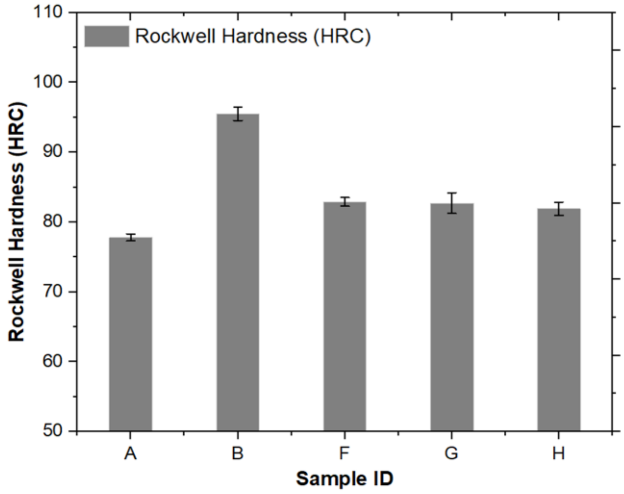


Fig. 6. Effect on the Rockwell hardness for WHT (A), QCH (B) and MTT (F, G and H).

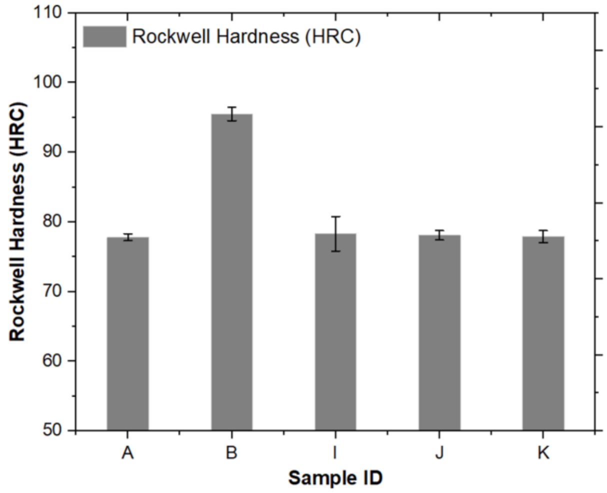


Fig. 7. Effect on the Rockwell hardness for WHT (A), QCH (B) and HTT (I, J and K).

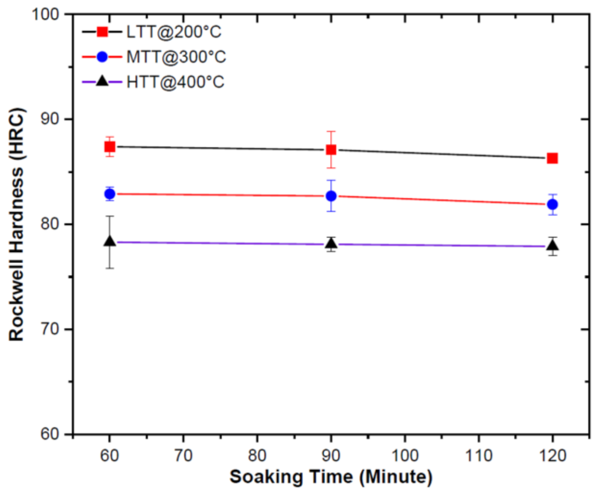


Fig. 8. Rockwell hardness behaviour of heat-treated (LTT, MTT and HTT) samples.

that tempered steel's hardness decreases because of grain re-arrangement in the subsequent tempering heat-treatment process. With an increase in tempering temperatures, the developed martensite during quenching breaks faster, resulting in a decrement in hardness.

### 4.2. Tensile strength

The tensile test experimental results of A36 ASTM standard samples are shown in Table 3. The ultimate tensile strength and yield strength were measured. The experimental results of tensile tests of heat-treated specimens are shown in Figs. 9−11 for LTT, MTT, and HTT conditions, respectively.

The results showed that the quenching process had improved both the ultimate tensile strength and yield strength by 31.51% and 32%, respectively, compared to the material samples without quenching. At the same time, the elongation has decreased from 17.04% to 15.39% compared to the samples without quenching. It has also been observed that the tempering with different soaking times has an insignificant effect on ultimate tensile strength, yield strength, and percentage of elongation. The strength of the samples dropped significantly due to the tempering process. This is possibly due to relieving the developed internal stresses and breaking down the martensite. Whereas the percentage of elongation increases due to improvement in ductility.

From Fig. 12, it can be clearly observed that the tensile strength decreases with an increase in the tempering temperature. Although the soaking time has an insignificant effect on the material's tensile strength.

### 4.3. Impact strength

The impact test experimental results of ASTM standard samples are shown in Table 4. The samples' impact strength at different conditions is shown in Figs. 13−15.

It has been observed that the impact strength of the quenched sample (B) dropped by 27.27% in comparison to the non-

Table 3. Tensile strength of A36 low-carbon steel.

| Sample ID | Heat treatment process[#] | Heating condition (°C/min) | Ultimate tensile strength (MPa) | Yield strength (MPa) | Elongation (%) |
|---|---|---|---|---|---|
| A | WHT | – | 76.2 | 78.5 | 78.8 |
| B | QCH | 900 / 120 | 97.2 | 95.4 | 93.8 |
| C | LTT | 200 / 60 | 87.9 | 86.3 | 88.1 |
| D | LTT | 200 / 90 | 86.8 | 85.5 | 89.0 |
| E | LTT | 200 / 120 | 86.9 | 85.9 | 86.2 |
| F | MTT | 300 / 60 | 83.9 | 81.8 | 82.9 |
| G | MTT | 300 / 90 | 85.2 | 80.2 | 82.8 |
| H | MTT | 300 / 120 | 79.3 | 82.6 | 83.8 |
| I | HTT | 400 / 60 | 77.5 | 81.2 | 76.3 |
| J | HTT | 400 / 90 | 76.6 | 79.4 | 78.4 |
| K | HTT | 400 / 120 | 79.6 | 77.7 | 76.3 |

[#]WHT – without heat treatment, QCH – quenching, LTT – low temperature tempering, MTT – medium temperature tempering, HTT – high temperature tempering.

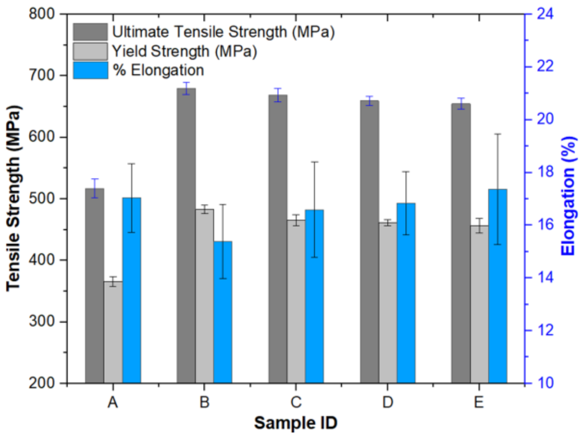


Fig. 9. Effect on the tensile strength for WHT (A), QCH (B) and LTT (C, D and E).

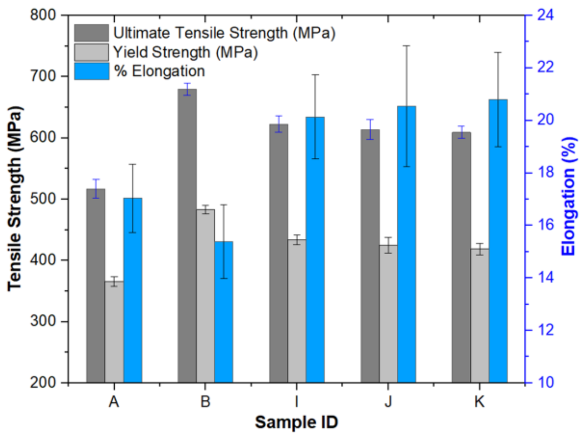


Fig. 11. Effect on the tensile strength for WHT (A), QCH (B) and HTT (I, J and K).

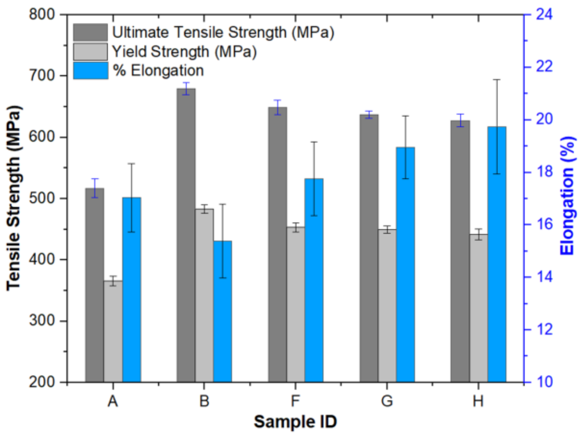


Fig. 10. Effect on the tensile strength for WHT (A), QCH (B) and MTT (F, G and H).

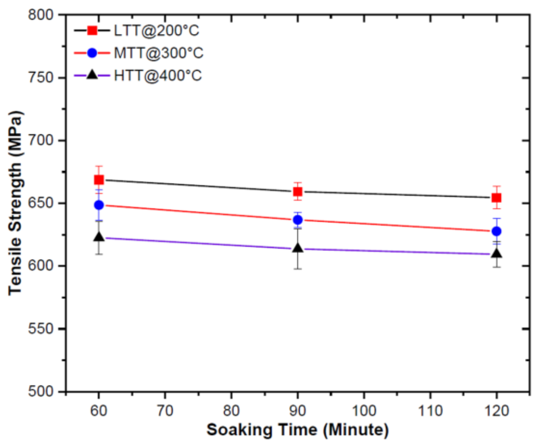


Fig. 12. Tensile strength behaviour of heat-treated (LTT, MTT and HTT) samples.

quenched sample (A). Due to the quenching process, residual stresses developed, resulting in increased material brittleness and decreased toughness. The subsequent tempering process of the sample material developed martensite and relieved the internal stresses, resulting in a significant improvement in the material's impact strength. The maximum improvement in impact strength of the material is 63.6% and 125% for HTT in comparison to samples without heat-treatment (A) and quenched samples (B), respectively (refer to Fig. 15).

Table 4. Impact strength of A36 low-carbon steel.

| Sample ID | Heat treatment process# | Heating condition (°C/min) | Impact energy (J) | Impact strength (kJ/m²) |
|---|---|---|---|---|
| A | WHT | – | 88 | 1100.0 |
| B | QCH | 900 / 120 | 64 | 800.0 |
| C | LTT | 200 / 60 | 72 | 900.0 |
| D | LTT | 200 / 90 | 79 | 987.5 |
| E | LTT | 200 / 120 | 88 | 1100.0 |
| F | MTT | 300 / 60 | 103 | 1287.5 |
| G | MTT | 300 / 90 | 115 | 1437.5 |
| H | MTT | 300 / 12. | 121 | 1512.5 |
| I | HTT | 400 / 60 | 133 | 1662.5 |
| J | HTT | 400 / 90 | 140 | 1750.0 |
| K | HTT | 400 / 120 | 144 | 1800.0 |

#WHT – without heat treatment, QCH – quenching, LTT – low temperature tempering, MTT – medium temperature tempering, HTT – high temperature tempering.

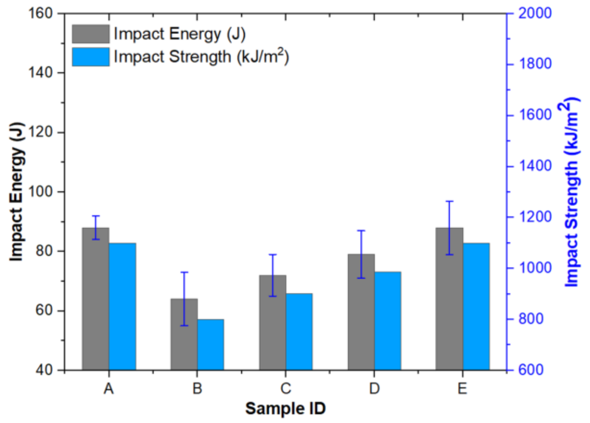


Fig. 13. Effect on the impact strength for WHT (A), QCH (B) and LTT (C, D and E).

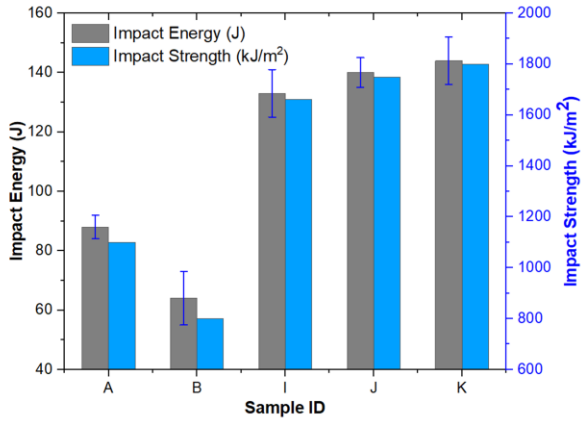


Fig. 15. Effect on the impact strength for WHT (A), QCH (B) and HTT (I, J and K).

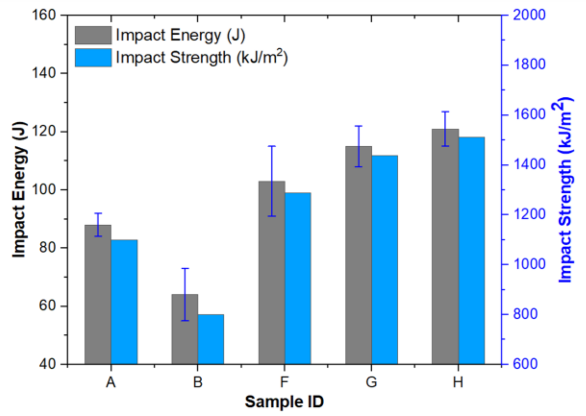


Fig. 14. Effect on the impact strength for WHT (A), QCH (B), and MTT (F, G and H).

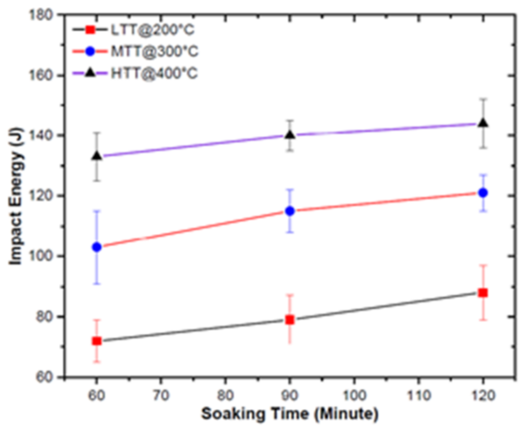


Fig. 16. Impact strength behaviour of heat-treated (LTT, MTT and HTT) samples.

The effect of tempering temperature and soaking time can be seen in Fig.16. It is also observed that with the increase in tempering temperature and soaking time, the impact strength of the material increases. The maximum impact strength of the test material is 144 J for HTT with a soaking time of 120 min. The material had sufficient time to eliminate the internal stresses.

## 5. Conclusions

The experimental investigation of the effect of heat treatment on low-carbon steel A36 has been carried out. The tests of Rockwell hardness, tensile strength, and impact strength of the ASTM A36 specimens were performed. The results state that the mechanical properties of low-carbon steel depend on heat treatment operations, heating temperatures above or below the critical temperature, and soaking time at a specific temperature. The following significant conclusions are drawn from this study.

- The Rockwell hardness of the samples is improved by 22.75% due to the heat treatment of the material.
- The quenching process improved the ultimate tensile strength and yield strengths by 31.51% and 32%, respectively, compared to those obtained without quenching. At the same time, the elongation decreased from 17.04% to 15.39%.
- Low, medium, and high temperature tempering at various soaking times released the internal stresses, refined the grain structure and exhibited the effects on tensile strength, and improved the elongation at break by 35.08% compared to quenched steel.
- The impact strength of the samples dropped by 27.27% due to quenching compared to the non-quenched sample. However, the subsequent tempering process of the samples improved the material's impact strength by 63.6% and 125% for HTT compared to samples without heat-treatment and quenched samples, respectively.

Therefore, the improved mechanical properties of A36 low-carbon steel through quenching and tempering make it highly suitable for structural applications, including construction, automotive, and machinery components. The increased hardness and tensile strength enhance wear resistance, while tempering at different temperatures optimises toughness and ductility, reducing the risk of failure under dynamic loads. These findings provide valuable insights for industries aiming to balance strength, toughness, and manufacturability in low-carbon steel applications.

The potential areas for further study may include investigating the effect of varying quenching temperatures on the microstructure and mechanical properties of A36 low-carbon steel. Additionally, incorporating different alloying elements such as chromium, nickel, or vanadium could enhance specific properties such as wear resistance, corrosion resistance, and toughness. Future studies could also explore the influence of alternative quenching media and advanced heat-treatment techniques to optimise the performance of A36 steel for diverse industrial applications.

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