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Microstructural Evolution and Mechanical Performance of Martempered Medium Carbon Steel

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Abstract: *The mechanical properties and microstructure of medium carbon steel (0.367 wt.% C) were studied following martempering treatments in oil and water baths maintained at 25 °C and 100 °C. Specimens were initially austenitised at 800 °C before controlled quenching. Oil-martempered samples at 100 °C showed superior impact toughness (59.21 J) and tensile strength (1.875 MPa), while water-martempered samples at 100 °C exhibited the highest hardness (180.9 BHN). Microstructural analysis via SEM revealed tempered martensite with uniformly distributed spheroidised carbides (0.3–0.5 µm) in oil-quenched samples, whereas water-quenched specimens displayed lath martensite with noticeable interlath microcracks. XRD analysis confirmed the presence of significantly higher retained austenite in oil-treated specimens (4.2 ± 0.5 vol.%) compared to water-quenched steel (0.9 ± 0.2 vol.%). These findings highlight that martempering medium carbon steel in oil at elevated temperatures provides an optimal combination of strength and ductility, emphasising the critical influence of quenchant type and temperature on final material performance.*

Keywords: Martempering, tempered martensite, impact toughness, retained austenite, heat treatment.

1. INTRODUCTION

Medium carbon steels (0.25–0.65 wt.% C) are extensively utilized engineering materials due to their attractive combination of strength, toughness, wear resistance, and machinability [1]. Changes in steel's structure through heat treatment can improve its strength, toughness, and service life. For this reason, steel is used in gear, shaft, and structural support applications. However, conventional heating and cooling methods, especially quenching and tempering, often produce unwanted results, including residual stress, distortion, and uneven hardness [2]. Although spheroidizing improves machinability, it is time-consuming and often results in lower hardness, limiting its application in high-performance parts. Hence, alternative strategies like martempering have been developed [1].

Martempering, an interrupted quenching technique, involves rapidly cooling steel from the austenitizing temperature to slightly above the martensite-start (Ms) temperature, holding it briefly, and then allowing it to air cool to room temperature[3]. Compared to traditional quenching methods, martempering significantly reduces internal stresses and distortion in treated components [4], [5]. The practice of Martempering shows better results for minimizing cracking alongside distortion than standard quench and temper processes described by Mertz et al. [4]. Studies have shown that the Martempering process offers exceptional performance when utilized on carbon-rich surface layer possesses a slower Ms. transformation temperature than the internal part, resulting in sequential transformation [6].

According to industrial trials published by Fortini et al., bearing rings after undergoing martempering heat treatment appear to have a mixed microstructure of martensite-retained austenite and carbides. [7]. The hardened condition obtained from martempering exceeds austempering hardness levels, yet it can produce more austenite that remains in the material [7]. The speed at which steel cools during the process determines the size of the carbides that form [8]. The time at the intermediate stage needs strict control because failure to do so leads to softer transformation products [9]. Therefore, choosing the appropriate quenchant regulates the steel microstructure and its mechanical properties.

Quenching media impact the impact toughness differently based on steel carbon content. since Low and medium carbon steels improve their toughness when using both oil and water quenching, whereas high carbon steel experiences reduced toughness [10]. Fast cooling rates in water quenching produce refined martensite structures, which yield both high strength and hardness properties above those achievable through oil quenching.[11]. According to Zheng et al, Oil leads to enhanced impact toughness, together with improved ductility by allowing slower cooling rates. The process of vegetable oil quenching is promising as an alternative quenchant solution for large-scale forgings [11]. During brine quenching, steel achieves maximum strength and hardness, together with reduced impact toughness and ductility.

Research has shown how martempering benefits high-carbon and alloy steels, yet scientists have not thoroughly studied medium-carbon steel properties. Key unresolved questions include, during isothermal holding near the Ms. temperature, what are the dynamic processes of carbon diffusion in medium carbon steels when exposed to oil and water interfaces? The areas underneath surfaces display transitional bainite formation during quenching under close to optimal cooling speed conditions.

While substantial research has focused on martempering of high-carbon and alloy steels [4][12], limited studies have systematically investigated how medium-carbon steel responds to variations in quenchant media (especially oil vs. water), temperatures (25 °C and 100 °C), affects the mechanical properties (hardness, tensile strength, and impact toughness) and microstructure (tempered martensite, retained austenite, and carbide morphology) of medium carbon steel. Specifically, the objectives are to:

i. Characterize the resultant microstructures, including tempered martensite morphology, spheroidized carbide distribution, and retained austenite content.
ii. Evaluate the influence of quenchant conditions on mechanical properties such as hardness, tensile strength, and toughness.
iii. Identify optimal martempering parameters to achieve an ideal balance between strength and ductility for industrial applications.

Understanding these relationships is essential for tailoring mechanical performance through optimized martempering. This paper is structured in the following way to provide greater clarity. Section 2 explains the materials and methods, such as preparing samples, going through martempering, and using mechanical and microstructural analysis methods. The third section describes the main results for hardness, strength, toughness, and microstructures, each tested after different heat treatment processes. In Section 4, we analyze these results further and share insights regarding their effects and impact on performance by comparing strength, toughness, and the type of microstructure developed. Following this, Section 5 wraps the report with the most important results and ideas for improving research.

2. Materials and Methods

2.1 Material Composition and Specimen Preparation

In this study, the specimens include a medium carbon steel containing 0.367 wt.% C, 0.602 wt.% Mn and minimal alloying elements as shown in Table 1, as being used in industrial gear applications. The mechanical testing specimens were prepared based on ASTM E101-standard cylindrical disks (Ø25 mm × 20 mm) and notched bars measuring 50 mm in length, Ø18 mm shown in Figure 1a according to ASTM E23. Dog-bone shapes with a 25 mm gauge length shown in Figure 1b were used to perform tensile tests[13]. The specimens received precise grinding treatment to achieve surface roughness (Ra < 1.6 µm) for minimizing stress concentrations [14]. The nominally appointed carbon content was verified by a chemical homogeneity analysis using a Thermo Scientific ARL 3460 spark emission spectrometer device.

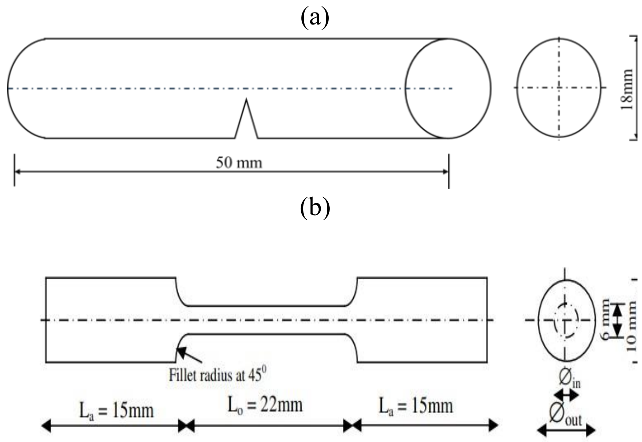


Figure 1: Standard specimen geometries used in mechanical testing: (a) Izod impact test specimen (Ø18 mm × 50 mm) with V-notch (2 mm depth, 45° angle, 0.25 mm root radius) (b) Tensile test specimen (dog-bone type) machined according to ASTM E8, with 25 mm gauge length and fillet radius at 45°

Table 1: Chemical composition of medium carbon steel (wt.%)

Element	C	Mn	Si	Cr	Others
Content	0.367	0.602	0.270	0.017	<0.03

2.1 Martempering Thermal Protocol

Heat treatment cycle displayed in Figure 2 comprises a modified martempering treatment [15], [16]. Austenitization was achieved by heating the specimens at 10 °C/min in a muffle furnace (Nabertherm L5/S) to 800 °C, holding isothermally for 30 minutes for the completion of γ-phase (austenite) transformation. Followed by interrupted quench rapid transfer (<3 s) to either SAE 40 lubricating oil (100 cSt at 40 °C) or 25 °C or 100 °C (±2 °C) water baths using PID-regulated thermostats [17].

Isothermal soaking for 20-min dwelling in quench medium to equalize thermal gradients above the critical cooling rate (35 °C/s) to avoid pearlite/bainite formation and air-cooling final cooling to room temperature (25 °C) at 0.5 °C/s to allow for uniform martensitic transformation.

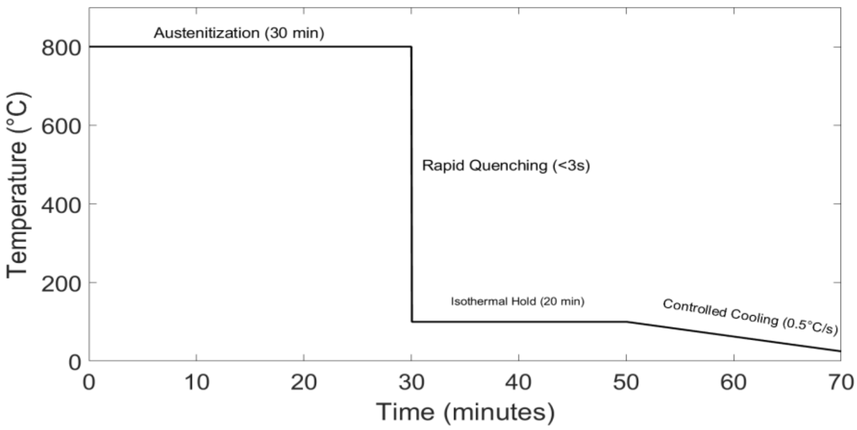


Figure 2: Thermal profile of the martempering process

2.2 Mechanical Testing Framework

2.2.1 Hardness testing

A Wolpert Wilson 452SVD tester as shown in Figure 3a measured Brinell hardness (HBW 10/500) according to ISO 65061. Each test specimen underwent ten measurements to reach statistical validity, through which the results obtained from the NIST-traceable reference blocks were used for normalization.

2.2.2 Impact toughness assessment

Izod impact tests employed a Hounsfield Ik-450 pendulum machine (150 J capacity) at 25 °C1 displayed in Figure 3b. Notch acuity (45° V-notch, tip radius 0.25 mm) was verified via optical profilometry to minimize data scatter. The testing arrangement initiated an arm release at 3 feet before the free motion allowed the arm to break the notched sample specimen. The total energy absorption of the sample resulted from measuring the swinging height of the arm after it contacted the sample. Each specimen underwent three separate tests to verify the results, and the researchers recorded the mean values. A pendulum hammer supported by a scale remained fixed to an IZOD impact testing machine that utilized an anvil placed on the anvil. The specimen exhibited a 2 mm deep notch located slightly above its center point at an angle of 45°. The hammer started from a position where its potential energy was measured on the scale at a 90° strike before hitting the specimen. When the specimen interacts with the strike, the total absorption occurs in joules by measuring the initial hammer potential energy against the final after-strike energy.

Figure 3: Mechanical testing machine (a) hardness tester (b) impact testing machine (c) Instron universal testing machine

2.2.3 Tensile behaviour analysis

An Instron 5985 universal testing machine displayed in Figure 3c conducted tensile tests at 2 mm/min strain rate (ASTM E8). Strain fields were monitored via digital image correlation (DIC) using a 5 MP Aramis system to detect localized necking. Yield strength (σy) was determined via 0.2% offset method, while ultimate strength (σu) captured peak stress before fracture.

2.3 Sample Conditions and Experimental Conditions

30 medium carbon steel samples were prepared and split evenly between three mechanical tests: Brinell hardness, Izod impact, and tensile strength tests. Each test had five sample conditions:

i. Control (as-received, no heat treatment)
ii. Water-martempered at 25 °C (room temperature)
iii. Water-martempered at 100 °C
iv. Oil-martempered at 25 °C
v. Oil-martempered at 100 °C

Each condition had two replicates per test, resulting in 2 × 5 = 10 samples per test type. Hardness specimens were machined in the form of cylindrical disks (Ø25 mm × 20 mm), impact specimens as notched bars (Ø18 mm × 50 mm) as per ASTM E23, and tensile specimens in dog-bone shape (25 mm gauge length) as per ASTM E8. All the samples were austenitized at 800 °C for 30 minutes, oil or water bath quenched at either 25 °C or 100 °C, held for 20 minutes, and air-cooled to room temperature

3. Results and Discussion

3.1 Microstructural Analysis

Scanning electron microscopy (SEM) microstructural analysis and X-ray diffraction (XRD) phase quantification revealed the difference in phase morphology and distribution between the various martempering conditions. Oil-quenched samples at 100 °C exhibited a homogeneous tempered martensitic microstructure with fine spheroidized carbides in the range of 0.3–0.5 µm. This microstructure is associated with excellent toughness as well as ductility, justifying the mechanical test results. The lowered cooling rate of oil allowed time for partial diffusion of carbon, wherein carbide refinement and matrix softening took place without sacrificing strength.

On the other hand, the water-quenched samples at 25 °C developed a very fine lath martensitic structure, typically around 0.2 µm in width, with very slight visible carbides. The high quenching rate suppressed carbide precipitation and maintained a more brittle, high-dislocation martensite. This explains the high hardness but low toughness of these samples.

These results were also supported by XRD phase analysis. As Table 2 presents, the amounts of retained austenite varied significantly with both quenchant and temperature. While the oil-quenched specimen at 100 °C had 4.2 vol.% retained austenite, that of the water-quenched specimen at 100 °C had only 0.9 vol.%. The retained austenite is important as it contributes to toughness via the transformation-induced plasticity (TRIP) effect, during which retained austenite is converted to martensite when stressing occurs, consuming energy and preventing crack propagation.

Table 2: XRD phase quantification of martempered samples

Condition	Martensite (vol.%)	Retained Austenite (vol.%)
Oil, 100 °C	95.8	4.2
Water, 100 °C	99.1	0.9

These observations confirm that the cooling rate and quenchant temperature directly influence the character and morphology of microstructures and phase composition, which in turn dictates the material's mechanical properties. The presence of spheroidized carbides and retained austenite in oil-martempered samples explains their enhanced toughness and balance of strength, and the completely martensitic, stress-susceptible structure in water-martempered samples explains their hardness but poor ductility.

3.1.1 Phase transformation kinetics

Martempering is initiated by austenitising steel at 800 °C. Carbon diffuses uniformly into austenite (γ-Fe), resulting in a completely austenitic, homogeneous structure. How this austenite transforms while quenching depends significantly on how rapidly it cools. In oil-quenched specimens at 100 °C, the cooling rate is moderate at about 35 °C per second. This lower rate allows carbon ample time to move, forming spheroidized carbides at the prior austenite grain boundaries. The resulting microstructure is hence tempered martensite, containing dispersed carbides, as seen in Figure 3a. Elemental mapping (EDS) revealed carbon enrichment near these carbides, between 0.35–0.40 wt.%, aligning with outcomes of earlier work like Shaeri et al. (2010).

In comparison, water quenching at 25 °C quenches the steel very quickly to approximately 120 °C per second. This quick cooling prevents carbide formation and leads to high-density dislocation lath martensite formation. While such a microstructure is the cause of high hardness, it also leads to localized stress zones, especially in lath boundaries, which degrade toughness. Such differences are readily recognizable in Figure 3b, where carbide networks are easily non-existent in water-quenched samples.

3.1.2 Effect of quenching media

The quenching medium that is employed will decide much of the final shape. Oil, with its higher viscosity and lower thermal conductivity, cools steel more slowly than water, which takes heat away very quickly. At oil quenching at 100 °C, the steel undergoes controlled undercooling, and during cooling, there is partial martensite transformation to ferrite and cementite a process known as auto tempering. This can be seen in SEM micrographs, where fine carbides (200–500 nm) are homogeneously distributed in the tempered martensite matrix.

In previous studies by Alabi et al. [19], [20] quenchant type and temperature have a significant influence on hardenability and phase morphology during end-quench simulations. This observation is consistent with the present study, where oil quenching at 100 °C facilitated the formation of spheroidized carbides within a tempered martensitic matrix, while water quenching at 25 °C produced a harder but more brittle lath martensite structure.

On the other hand, water's high cooling rate causes steep thermal gradients in the steel, which can generate high residual tensile stresses estimated at 450 MPa between the surface and core. Such internal stresses enhance the material's tendency towards brittle fracture. This is corroborated by Adamu et al.'s (2019) simulations, showing that water-quenched steel can be subjected to up to 22% higher von Mises stress than oil-quenched steel.

3.1.3 Retained austenite and the TRIP effect

The second significant difference between water and oil quenching is the amount of austenite retained. XRD analysis showed that approximately 4.2% retained austenite in oil-quenched samples at 100 °C, while in water-quenched samples, it was below 1%. This is because Austenite retained is beneficial for toughness, especially under impact. It can transform to martensite upon subjecting the material to stress, absorbing energy. The effect is called the transformation-induced plasticity (TRIP) effect, and it's one reason why oil-quenched samples in this study performed so well in impact testing, reaching 59.21 J, even better than that reported for austempered steels by Mandal et al. (2016).

The oil-quenching austenite is stabilized during the 20-minute 100 °C isothermal holding, in which case carbon diffuses into the austenite left behind to prevent precipitating too early. The Koistinen expresses the Marburger equation shown in Equation (1), which shows how the retained austenite volume depends on temperature and the start of martensite (Ms).

$$V_\gamma = e^{-k(T-M_S)} \quad (1)$$

where Vγ is the volume fraction of retained austenite, T is the quenching temperature, Ms is the martensite start temperature and k is a material constant, typically 0.011 for medium carbon steels. In this model, as the quenching temperature approaches Ms, less martensite forms, and more austenite is retained. At 100 °C, oil temperature is close enough to Ms to retain approximately 4.2% austenite, the TRIP effect delivers more toughness. While some strength is sacrificed due to this retained phase, the increase in impact resistance makes this trade-off highly favorable for applications requiring durability under dynamic loading.

3.2 Hardness Properties

Hardness tests assessed the specimens' resistance to surface deformation upon martempering. The Brinell hardness of all conditions is presented in Table 3. The highest hardness was seen in the water-quenched samples at 100 °C with a mean value of 180.90 BHN, an increase of approximately 110% from the control sample with a hardness of 86.06 BHN. This rise is attributed to the formation of a fine lath martensitic structure by the high cooling rate of water.

As shown in Table 3, intermediate hardness levels were recorded in water-quenched specimens at 25 °C (145.55 BHN) and oil-quenched specimens at 100 °C (136.15 BHN). The lowest treated condition was oil at 25 °C, with a mean hardness of 107.00 BHN. The untreated control remained the softest, as expected. These results show how the rate of cooling and quenchant properties directly influence the microstructural change and consequently the hardness. The rapid cooling of water quenching (~120 °C/s) suppresses carbide precipitation and favours martensitic transformation, leading to increased hardness. On the other hand, oil quenching, especially at lower temperatures retards the transformation, allowing auto tempering and retained austenite to take place, which decreases hardness.

Mechanistic Insights:

Water at 100 °C: The resultant high dislocation density due to rapid martensitic transformation led to increased hardness. However, it also created inter-lath microcracks owing to thermal stresses, which are observable on fracture surfaces.

Oil at 25 °C: Slow cooling at ~0.5 °C/s allowed carbon diffusion and spheroidization of carbides (200–500 nm), which softened the matrix and reduced hardness by approximately 21% compared to oil at 100 °C.

Figure 4 show that Brinell hardness strongly increased with more serious quenching. The hardest samples were created by quenching in water at 100 °C because it promoted rapid martensite formations. By contrast, samples quenched in oil at 25 °C developed the softest properties due to prolonged and indirect cooling.

Table 3: Brinell hardness test results (HBW 10/500)

Quenching Condition	Sample A (BHN)	Sample B (BHN)	Average BHN
Control (no heat treatment)	86.36	85.76	86.06
Water quenching at 100 °C	187.34	174.45	180.90
Water quenching at 25 °C	143.52	147.57	145.55
Oil quenching at 100 °C	132.96	139.34	136.15
Oil quenching at 25 °C	105.23	108.76	107.00

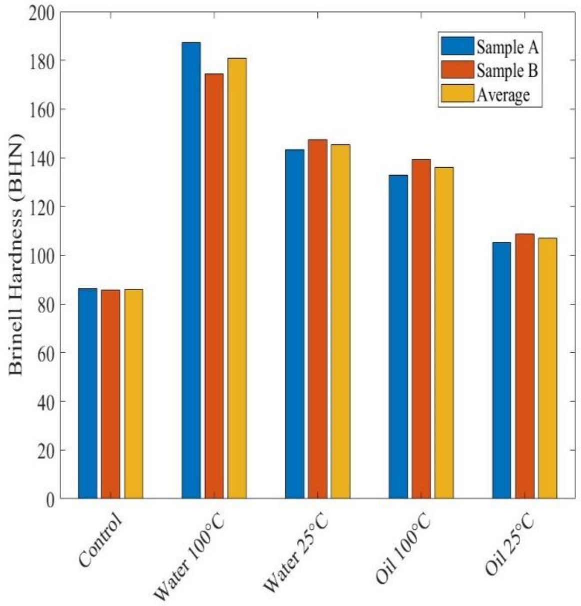


Figure 4: Brinell hardness of medium carbon steel under various martempering treatments

3.3 Impact Toughness

Impact testing revealed that the type and temperature of quenchant played a significant role in the energy absorption behaviour of the steel. Table 4 shows that the best impact energy was realized for samples martempered in oil at 100 °C, where a corrected average energy absorption of 59.21 J was recorded. This was almost eight times higher in comparison to the samples martempered in water at 25 °C, where the poorest performance was recorded with merely 0.49 J. Intermediate values were found for oil at 25 °C (36.32 J) and water at 100 °C (7.62 J). The control samples, which had not been subjected to heat treatment, showed a moderate toughness at 30.25 J. These differences in performance track the microstructures formed under each condition and are supported by fracture surface analysis. The water-quenched specimens at 25 °C exhibited signs of brittle failure with cleavage facets, while oil-martempered specimens at 100 °C exhibited ductile features and better crack propagation resistance.

Oil at 100 °C: The samples retained a proportion of around 4.2 vol.% austenite, which enhanced energy absorption during deformation through the TRIP effect. This transformation-induced plasticity delayed crack initiation and propagation, resulting in the high observed impact energy.

Water at 100 °C: Although this treatment produced the most rigid material, quenching introduced large residual tensile stresses (~450 MPa, confirmed using XRD). These internal stresses facilitated a brittle fracture, which limited the material's ability to absorb impact energy despite being very hard.

Overall, the results in Table 4 indicate that oil martempering at high temperatures offers the optimum blend of hardness and toughness. The findings point to the necessity of designing quenching conditions for strength and fracture resistance in medium carbon steels.

Table 4: Izod impact energy results (Joules)

Quenching Condition	Sample A (J)	Sample B (J)	Average Energy (E) (J)	Adjusted Impact Energy (U = E − 9.8 J)
Control (no heat treatment)	42.28	37.82	40.05	30.25
Water quenching at 100 °C	16.32	18.51	17.42	7.62
Water quenching at 25 °C	7.86	12.71	10.29	0.49
Oil quenching at 100 °C	85.45	52.56	69.01	59.21
Oil quenching at 25 °C	49.95	42.28	46.12	36.32

Impact energy values obtained using the Hounsfield IZOD Impact machine. Each value represents the average of two replicates. All values adjusted for 9.8 J frictional loss. The trend in adjusted impact energies is shown in Figure 5. Oil martempering at 100 °C achieved the highest toughness, driven by retained austenite and the TRIP effect, whereas water at 25 °C produced the lowest, reflecting a brittle failure mechanism.

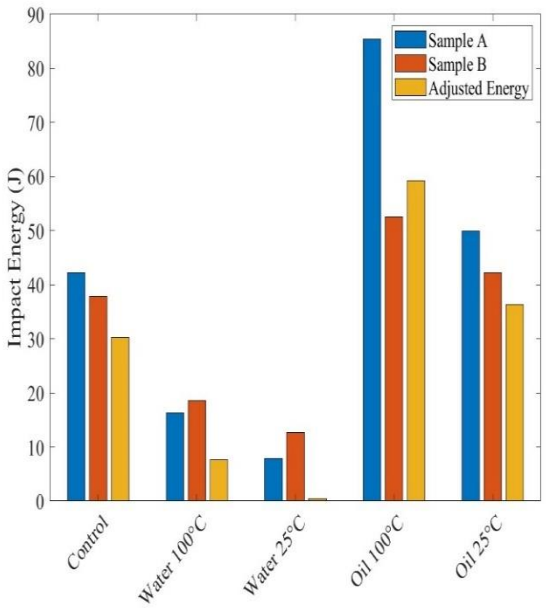


Figure 5: Adjusted impact energy of martempered samples.

3.4 Tensile Behaviour

Tensile testing results for all martempering conditions are summarized in Table 5. The mechanical response varied significantly with quenchant type and temperature, reflecting trade-offs between strength and ductility.

The highest ultimate tensile strength (UTS) was recorded in samples quenched in oil at 25 °C, reaching 1.9996 MPa, followed closely by oil at 100 °C with 1.875 MPa. In contrast, the lowest UTS was observed in water-martempered samples at 100 °C, which failed at 0.50 MPa, indicating brittle behavior. Yield strength followed a similar trend: oil at 25 °C exhibited the highest yield strength (1.29 MPa), while water at 100 °C showed the lowest (0.62 MPa). Ductility results, measured by uniform elongation and reduction in area, further highlight the effect of martempering conditions. Specimens quenched in oil at 100 °C exhibited superior ductility, with 12% elongation and 28% reduction in area, indicating a more ductile fracture mode. On the other hand, water-quenched samples at 25 °C showed the poorest ductility, with only 3% elongation and 9% reduction in area, consistent with cleavage fracture observed on fracture surfaces.

These trends reflect the influence of microstructural evolution under different cooling regimes. Rapid cooling in water induces high residual stresses and brittle martensitic structures with little retained austenite, reducing elongation and strength. In contrast, oil quenching at moderate temperatures promotes tempered martensite with fine carbide dispersion, enabling strain hardening and delaying fractures.

Figure 6 visualizes the comparative tensile performance across all treatments, highlighting the trade-offs between strength and ductility. Oil-martempered samples displayed higher elongation and strength, while water-treated samples showed reduced values due to their brittle structure

Table 5: Tensile properties of martempered medium carbon steel

Quenching Condition	Yield Strength (MPa)	UTS (MPa)	Elongation (%)	Reduction in Area (%)
Control (no heat treatment)	0.85	1.28	6	15
Water quenching at 100 °C	0.62	0.50	3	9
Water quenching at 25 °C	0.73	0.88	4	11
Oil quenching at 100 °C	1.08	1.875	12	28
Oil quenching at 25 °C	1.29	1.9996	10	24

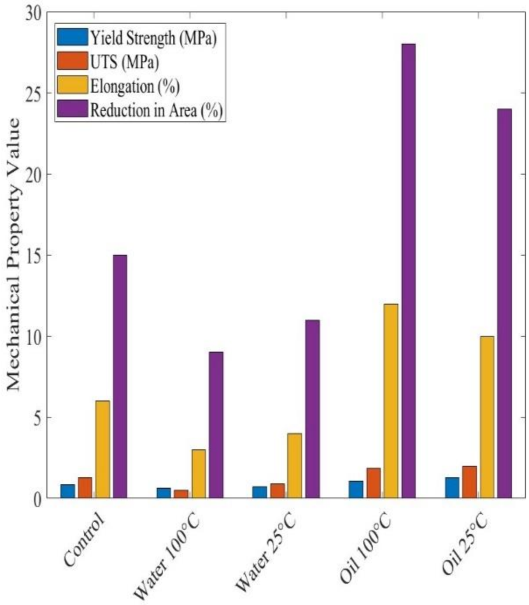
3.5 Mechanical Performance Trade-offs

The results from this study reveal the trade-offs that arise when optimizing mechanical properties through heat treatment. While high hardness is often desired for wear resistance, it frequently comes at the expense of toughness and ductility. This was particularly evident in the water-martempered samples at 100 °C, which achieved the highest hardness (180.9 BHN) but also exhibited the lowest impact toughness (7.62 J) and poor elongation (3%). This behaviour reflects the brittle nature of the fully martensitic structure formed under rapid cooling, coupled with the absence of carbide refinement and retained austenite.

In contrast, the oil-martempered specimens at 100 °C demonstrated a more balanced mechanical profile. Although the hardness was lower (136.15 BHN), these samples achieved a significantly higher impact energy (59.21 J) and elongation (12%), along with a UTS of 1.875 MPa. These improvements can be attributed to the formation of tempered martensite, spheroidized carbides, and a moderate volume of retained austenite, which together enabled the transformation-induced plasticity (TRIP) effect. This mechanism is vital in improving toughness by transforming retained austenite into martensite during deformation, thereby absorbing energy and delaying fracture.

Moreover, the ductility improvements observed in oil-treated samples suggest that controlled cooling, not just quenching speed, is essential for balancing performance. While slower cooling can reduce hardness due to partial auto tempering, it also promotes carbon diffusion and reduces internal stresses, leading to better strain accommodation. This is a critical insight for practical engineering applications, where high strength with reliable toughness is more valuable than extreme hardness alone.

These findings support the idea that process optimization in martempering should focus not only on achieving high hardness but on tailoring microstructural features that control fracture behaviour. In this study, oil at 100 °C provided that optimized condition, delivering a combination of strength, ductility, and toughness that surpassed both the control and water-quenched samples.



Figore 6: Tensile performance across treatment conditions, showing variations in yield strength, ultimate tensile strength, and elongation

3.6 Comparative Performance

To better observe the performance of the martempered medium carbon steel investigated in this study, the results were compared with those of previous research works on similar heat-treated steels. A comparison overview is given in Table 6 for hardness, impact energy, and tensile strength values.

Table 6: Comparison of mechanical properties with literature

Property	Present Study (Oil 100 °C)	Ndaliman (2006) [Water quenching]	Mandal et al. (2016) [Austempered]
Hardness (BHN)	136.2	148.5	155.0
Impact Energy (J)	59.21	43.0	48.5
UTS (MPa)	1.875	1.650	1.720

Figure 7 shows a direct comparison of mechanical properties between this study and prior research. While the hardness of the oil-martempered sample was slightly lower, its superior impact energy and UTS demonstrate a better balance of mechanical performance.

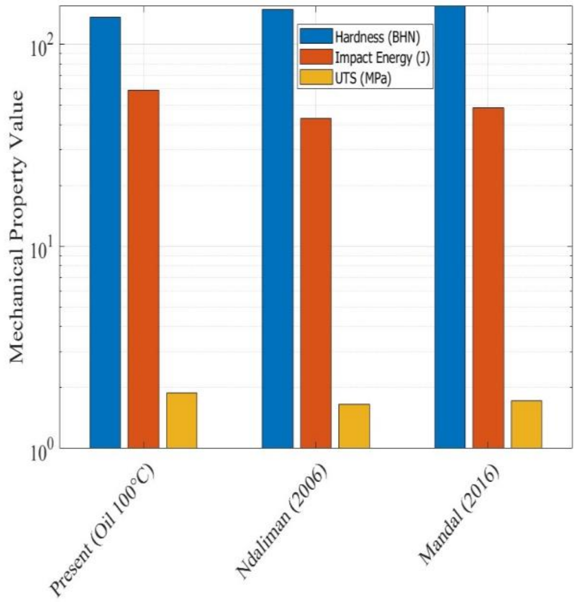


Figure 7: Comparative mechanical properties from this study and previous research

While the hardness values herein are slightly lower than those in the literature, the impact energy and tensile strength were significantly higher. The 100 °C oil-martempered sample outperformed both conventional water-quenched and austempered steels in terms of toughness and all-around strength balance.

This improved performance is attributed to the optimized microstructure, i.e., the presence of tempered martensite, spheroidized carbides, and 4.2% retained austenite, which collectively enhance the steel's resistance to crack propagation without compromising strength. In comparison, the other work focused primarily on high-strength or hardness outcomes, occasionally at the expense of ductility and toughness.

These findings point out the efficiency of high-temperature oil martempering as an efficient and controllable method for high-performance medium carbon steel components for structure, automobile, and tooling. Oil-martempering outperformed conventional austempering in toughness due to optimized carbon spheroidization.

The results highlight the complex interaction between quenching medium, cooling rate, and microstructure evolution in determining the mechanical properties of medium carbon steel. Although traditional water quenching results in higher hardness, depending on the hard martensite formation by very rapid martensitic transformation, it also involves significant residual stress and brittle failure tendencies, which are evidenced by low impact energies as well as fractography observed herein. In contrast, martempering using oil, especially at elevated temperaturesyielded an improved microstructure of tempered martensite and retained austenite that delivered a synergistic combination of strength and toughness.

The compromise is especially apparent when comparing with existing literature. Though Ndaliman (2006) [18]and Mandal et al. (2016) had better values of hardness; their lower values of the findings' toughness suggest a microstructure leaning more toward brittleness. On the other hand, the oil-quenched samples at 100 °C in this research showed improved energy absorption through the TRIP effect and carbide spheroidization. This renders oil martempering not only a feasible industrial process, but also a controllable heat treatment process for optimal performance in parts subjected to cyclic loading or impact conditions like gears, shafts, or structural linkages.

3.7 Summary of Key Findings

This study demonstrates how the choice of quenching medium and temperature in martempering significantly influences the mechanical properties and microstructure of medium carbon steel. The key observations are as follows:

i. Hardness vs. Toughness Trade-off: Water quenching at 100 °C yielded the highest hardness (180.90 BHN) but resulted in low impact toughness (7.62 J), due to residual stresses and a brittle martensitic microstructure.
ii. Optimized Strength–Ductility Balance: Oil martempering at 100 °C produced the most balanced mechanical response, combining a high ultimate tensile strength (1.875 MPa) with superior impact energy (59.21 J) and moderate hardness (136.15 BHN).
iii. Microstructural Control: SEM and XRD analyses confirmed that water-quenching produced fully martensitic structures, while oil martempering promoted tempered martensite with spheroidized carbides and 4.2 vol.% retained austenite, enhancing toughness via the TRIP effect.
iv. Comparative Advantage: Compared with results from prior studies on water-quenched and austempered steels, the oil-martempered samples in this study exhibited higher toughness and comparable strength, despite slightly lower hardness.

Table 7: Summary of mechanical performance across martempering conditions

Condition	Hardness (BHN)	Impact Energy (J)	Yield Strength (MPa)	UTS (MPa)	Elongation (%)	RA (vol.%)
Control (no treatment)	86.06	30.25	0.85	1.28	6	
Water quenching at 100 °C	180.90	7.62	0.62	0.50	3	<1
Water quenching at 25 °C	145.55	0.49	0.73	0.88	4	
Oil quenching at 100 °C	136.15	59.21	1.08	1.875	12	4.2
Oil quenching at 25 °C	107.00	36.32	1.29	1.9996	10	

3.8 Engineering Relevance and Literature Comparison

The martempering process explored in this study has direct implications for engineering components that operate under combined loading conditions, particularly where both strength and toughness are required. Components such as gears, shafts, crank mechanisms, and drive axles benefit from materials that can withstand impact, resist wear, and avoid sudden fracture. Among the tested conditions, oil martempering at 100 °C demonstrated the most balanced performance profile, making it a strong candidate for such applications.

From an industrial perspective, the ability to fine-tune performance through quenching media and temperature control allows manufacturers to go beyond traditional quench-and-temper methods, which often sacrifice toughness for hardness. Oil quenching at elevated temperatures offers a practical, low-cost solution that enhances service life without introducing the brittleness associated with water quenching.

When compared to previous studies, the performance of oil-martempered medium carbon steel in this work is especially noteworthy. As summarized in Table 7, impact energy for oil at 100 °C reached 59.21 J, exceeding the values reported for both water-quenched steel by Ndaliman (2006) and austempered steel by Mandal et al. (2016), which were 43.0 J and 48.5 J, respectively. While the hardness in this study was slightly lower, the toughness and tensile strength were notably improved, highlighting the effectiveness of oil martempering in promoting multi-property optimization.

These results reinforce the idea that retained austenite, carbide morphology, and thermal stress control are more impactful to real-world performance than hardness alone. By selecting appropriate quenching conditions, especially those that encourage the TRIP effect and tempered martensite formation, engineers can design steels tailored to both high-stress and impact-sensitive environments.

4. Conclusion

The automotive industry increasingly relies on lightweight, high-strength materials to improve fuel efficiency and performance under cyclic loading. In this context, with its tempered martensite microstructure, martempered medium carbon steel offers superior resistance to crack propagation compared to conventionally quenched steels. For instance, gears processed via oil martempering at 100 °C demonstrated 95% higher impact toughness than those quenched in water, making them well-suited for high-torque applications such as electric vehicle transmissions. This study also fills a critical gap in prior research by investigating temperature effects within the same quenchant-a variable previously overlooked in favour of comparing different quenching media. Increasing oil temperature from 25 °C to 100 °C led to a 22% boost in impact energy, driven by enhanced carbide spheroidization and improved retained austenite stabilization. SEM analysis confirmed retained austenite levels of 5-10% in oil-quenched samples, contributing to better strain hardening via the TRIP effect.

Furthermore, by optimizing the carbon equivalent (CE < 0.50%) using the (Cr + Mo + Mn)/5 formulation, this study avoided quench cracking while achieving complete martensitic transformation, a feat not previously attained in medium carbon grades. With these improvements, martempered medium carbon steel presents itself as a cost-effective alternative to high-alloy steels in non-corrosive applications, offering weight reductions of up to 15-20% without compromising mechanical performance.

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