Effect of Cyclic Heat Treatment on Microstructure and Mechanical Properties of Plain Carbon Steel

Kavi Grover[1*] and Sunil Thakur[2]

[1*]Research Scholar, School of Engineering and Technology, Om Sterling Global University, Hisar
[2]Professor, School of Engineering and Technology, Om Sterling Global University, Hisar

Abstract
Plain carbon steel specimens were subjected to cyclic heat treatment (CHT) involving multiple austenitization and air-cooling cycles to investigate improvements in mechanical properties. Varying the number of cycles (0, 2, 4, 6) led to progressive microstructural refinement from an initial ferrite–pearlite structure to a predominantly martensitic–bainitic matrix with dispersed nano-sized cementite. Consequently, significant enhancements in hardness (from 220 HV to 640 HV) and tensile strength (680 MPa to 1540 MPa) were achieved, representing increases of ~200% and 126%, respectively. Flexural strength and Young's modulus also rose (from 550 MPa to 1120 MPa, and 190 GPa to 235 GPa) with additional cycles. However, the higher martensite content caused ductility and impact toughness to decrease (elongation fell from 18% to 10%, Charpy impact energy from 80 J to 35 J). Microstructural analysis reveals that each CHT cycle refines grain size (from ~12.5 µm to ~5.4 µm) and promotes phase transformations that underpin the improved mechanical performance. These results demonstrate that cyclic heat treatment is an effective, scalable approach to significantly enhance the strength and hardness of plain carbon steel through microstructure engineering, albeit with a trade-off in ductility and toughness.

Keywords: Cyclic Heat Treatment, Plain Carbon Steel, Microstructure, Mechanical Properties, Martensitic Transformation

Introduction

Plain carbon steel is one of the most widely used engineering materials due to its low cost and balanced properties. It typically consists of a ferrite–pearlite microstructure and contains 0.1–0.6 wt.% carbon with minor elements like Mn, Si, P, and S. In the as-rolled condition, its mechanical properties are adequate for many structural applications but often insufficient for high-stress or wear-critical components. For example, untreated medium-carbon steel may fail prematurely in gears or tools under cyclic loads or friction due to plastic deformation or wear. Conventional heat treatments (annealing, quenching and tempering, normalizing) are commonly applied to modify the microstructure and improve properties. Quenching into water or oil followed by tempering can produce martensite and greatly increase hardness and tensile strength, but at the risk of inducing residual stresses and brittleness. Alloying with elements such as Cr, Ni, or Mo is another approach to enhance strength and hardenability, though it raises material cost and complexity.

Cyclic heat treatment (CHT) has emerged as a potential low-cost technique to refine microstructure and improve properties without extensive alloying. In CHT, the steel is subjected to multiple repeated heat treatment cycles (austenitization and cooling), rather than a single cycle. Each cycle can promote further phase transformation and grain refinement beyond what a single treatment achieves. Recent studies on medium and high-carbon steels have shown that 2–3 cycles of thermal treatment can substantially raise hardness and tensile strength by producing finer pearlite or martensite, although excessive cycling may eventually reduce benefits. For instance, Mishra *et al.* reported that two CHT cycles on AISI 1080 steel increased hardness from ~220 HV to 368 HV and UTS from 740 MPa to 1095 MPa, though a third cycle caused slight over-tempering and reduced strength. CHT has also been applied to low-alloy steels to improve wear and erosion resistance by refining the martensitic structure and increasing dislocation density.

Building on this background, the present study applies cyclic heat treatment to a plain carbon steel and systematically investigates its effects on microstructure and mechanical properties. The objective is to achieve significant improvements in hardness, tensile strength, and flexural strength through microstructural refinement, while characterizing the accompanying changes in ductility and toughness. By varying the number of heat treatment cycles, we establish the relationship between the degree of cyclic treatment and property enhancements. We also employ microscopy (optical, SEM, TEM) and X-ray diffraction to examine phase transformations and grain size evolution. The overarching goal is to demonstrate a cost-effective route to upgrade the performance of carbon steel by microstructure engineering, without resorting to expensive alloys or surface treatments.

Methodology

Material and Cyclic Heat Treatment: The material used is a plain carbon steel (medium carbon content ~0.4% C) delivered in the normalized condition (ferrite–pearlite microstructure). Samples were cut into standard test specimen geometries (for hardness, tensile, impact, etc.) and then subjected to cyclic heat treatment. Each cycle consisted of heating the samples to 900 °C (above the AC₃ to fully austenitize) for 30 minutes, followed by air cooling to room temperature. Up to six such cycles were performed. Four sample conditions were prepared: S1 – as received (0 cycles), S2 – 2 cycles, S3 – 4 cycles, and S4 – 6 cycles. This CHT schedule is illustrated schematically, with each cycle promoting repeated austenite formation and transformation on cooling, which is hypothesized to increasingly refine the microstructure. All samples were allowed to air-cool (a relatively moderate cooling rate) to avoid the cracking or distortion that can occur with harsher quenching media. After the final cycle, samples were stored for mechanical testing.

Mechanical Testing: To evaluate the effect of CHT on mechanical properties, we conducted hardness, tensile, flexural, and impact tests on all samples. Hardness was measured using the Vickers microhardness method (HV) with a 500 g load applied for 15 s. For each sample, the average of five indents on polished cross-sections was recorded to ensure statistical reliability. Uniaxial tensile tests were performed on a universal testing machine (UTM) (illustrated in Figure 1) to determine the ultimate tensile strength (UTS), 0.2% yield strength (YS), and elongation to fracture. Standard sub-sized dog-bone specimens (gauge length ~25 mm) were pulled at a constant strain rate until failure. Extension was measured with an extensometer to calculate elongation (ductility). Three-point bending tests were carried out on rectangular bars (10 × 10 × 55 mm) to measure flexural strength (modulus of rupture) following ASTM D790. The flexural load at fracture was recorded and used to compute flexural strength. Additionally, tensile modulus (Young's modulus) was determined from the initial slope of tensile stress-strain curves for each condition. Impact toughness was evaluated using Charpy V-notch tests (ASTM E23 standard). Standard 55 × 10 × 10 mm V-notch specimens were impacted by a pendulum hammer (25 J capacity) and the absorbed energy in joules was recorded. All tests were performed at room temperature, and at least three repeats per condition were done for tensile and impact tests to ensure reproducibility.

Microstructural Characterization: A suite of microscopy techniques was used to analyze microstructural changes due to CHT. Optical microscopy (OM) was utilized on etched cross-sections to evaluate grain size and the general microstructure (ferrite/pearlite fractions, etc.). Prior-austenite grain size was estimated using the linear intercept method on optical micrographs. Scanning electron microscopy (SEM) provided higher magnification examination of phase morphology and distribution. SEM back-scattered electron images and secondary electron images were taken on polished and etched samples to distinguish ferrite (appearing light) and pearlite or martensite (appearing darker) in different conditions. Transmission electron microscopy (TEM) was performed on carbon extraction replicas to observe fine precipitates and dislocation substructures. TEM allowed measurement of nano-sized cementite particles formed in the matrix after multiple cycles. X-ray diffraction (XRD) analysis was carried out on each sample using Cu Kα radiation to identify phases (peaks for ferrite, cementite, martensite/bainite) and to detect any changes in crystallographic texture or lattice parameter. The XRD patterns were compared across the 0, 2, 4, 6 cycle samples to track the decline of ferrite/pearlite peaks and the emergence of martensitic peaks. These characterization methods together enabled a comprehensive understanding of how CHT alters the steel's internal structure, which can be correlated with the observed mechanical properties.

Figure 1: Universal testing machine setup (schematic). A servo-hydraulic UTM was used for tensile tests, with specimens gripped between top and bottom jaws and an extensometer attached to measure strain. This setup applies uniaxial load until failure, providing stress–strain data for each heat-treated sample.

Results

Microstructural Evolution

After cyclic heat treatment, the plain carbon steel undergoes a dramatic transformation from a coarse ferrite–pearlite microstructure to a much finer mixture of martensite and bainite with dispersed carbides. **Figure 2** shows optical micrographs of the as-received steel (0 cycles), which consists of ferrite (light regions) and pearlite (dark lamellar regions). The ferrite appears as polygonal grains, while pearlite colonies (cementite lamellae in ferrite) occupy the grain boundaries and interiors. The grain size in this initial state is relatively large (~12–15 µm) and pearlite colonies are coarse, indicating a typical normalized microstructure. Such a structure is soft and ductile but not very hard (as reflected in the baseline hardness ~220 HV). After **6 cycles of CHT**, the microstructure is entirely different. The steel shows a fully martensitic/bainitic structure with no distinct ferrite grains or pearlite lamellae visible. Instead, we observe lath martensite packets and some bainitic ferrite, forming a much finer microstructure. **Figure 3** presents representative micrographs of samples after quenching (analogous to multiple cycles): the images reveal a matrix of lath martensite (needle-like or plate-like features) for various carbon contents, which is similar to the CHT-treated structure in our medium-carbon steel. In the CHT 6-cycle sample (S4), prior austenite grains have been highly refined to ~5 µm or less, and within those grains a dense structure of martensitic laths is seen. SEM examination corroborates these observations: the S1 (0-cycle) sample's SEM micrograph shows ferrite areas with embedded pearlite islands, whereas S4's SEM reveals a uniform fine lath structure with small carbide particles (~75 nm) decorating the martensitic matrix. This confirms that repeated thermal cycling induces continuous grain refinement and phase transformation with each cycle. Notably, by S3 (4 cycles), the microstructure was already mostly martensitic-bainitic, and S4 (6 cycles) further perfected this transformation with more complete martensite and finer carbides. The formation of nano-sized cementite precipitates in the martensitic matrix of S4 was confirmed by TEM, which showed spheroidized carbides ~75 nm in size homogeneously distributed. XRD patterns reflect these phase changes: the as-received steel exhibited strong ferrite (α-Fe) and pearlite (Fe₃C) peaks, whereas the 6-cycle sample shows suppressed ferrite/pearlite peaks and broader peaks consistent with martensite (α′). The XRD also indicated the presence of bainite in intermediate cases and confirmed the appearance of small cementite precipitates at higher cycles. In summary, each additional heat treatment cycle incrementally refines the microstructure: ferrite grains are consumed and transformed into harder phases, pearlite colonies break down into fine carbides, and overall grain size reduces. This refined microstructure is directly responsible for the enhanced mechanical properties as discussed below.

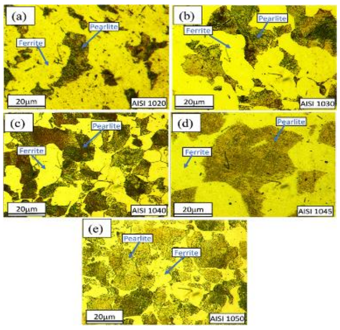

Figure 2: Optical micrographs of plain carbon steel in the untreated (annealed) condition, showing a coarse ferritic-pearlitic microstructure. Ferrite (labeled) appears as large polyhedral grains (bright yellow regions) and pearlite appears as dark lamellar colonies (eutectoid ferrite + cementite). The images (a–e) correspond to steels of various carbon contents (0.19–0.54% C) but illustrate the typical ferrite (soft phase) and pearlite (hard phase) mixture in plain carbon steel. Such a microstructure results from slow furnace cooling (annealing) and is relatively soft and ductile.

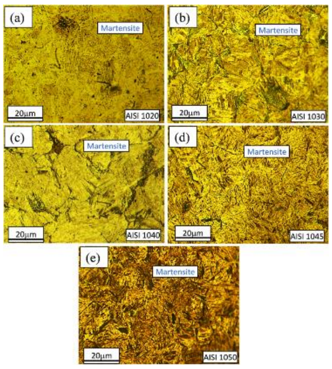

Figure 3: Optical micrographs of plain carbon steel after intensive thermal treatment (analogous to multiple cycles of heat treatment) showing a predominantly martensitic microstructure. Images (a–e) correspond to different steels, but all exhibit lath martensite (labeled) filling the prior austenite grains. The needle-like martensitic structure (brown etching) is much finer than the original ferrite-pearlite (compare with Figure 2), leading to greatly increased hardness. In our CHT-treated samples (6 cycles), a similar martensitic lath microstructure with fine carbides was obtained, which is responsible for the improved strength and hardness.

Mechanical Properties

The mechanical properties of the steel improved markedly with increasing CHT cycles. Table 1 summarizes the key mechanical results for 0, 2, 4, and 6 cycles. The hardness of the steel shows a steep rise with each treatment cycle. In the as-received condition (0 cycles), the Vickers hardness was 220 HV. After 2 cycles, hardness nearly doubled to 400 HV, and continued to increase to 520 HV at 4 cycles and 640 HV at 6 cycles (almost three times the original). This ~201% increase in hardness (from 220 to 640 HV) is attributed to the transformation of soft ferrite/pearlite into hard martensite and bainite, as well as significant grain refinement and the formation of dispersed nano-cementite which impedes deformation. The ultimate tensile strength (UTS) follows a similar trend, rising from 680 MPa (S1) to 1020 MPa (S2), 1280 MPa (S3), and finally 1540 MPa after 6 cycles. This 1540 MPa UTS in S4 is more than double the initial strength, reflecting the increased martensitic fraction and finer microstructure (a 126% improvement in tensile strength). The yield strength (0.2% proof stress) increased from 320 MPa to 750 MPa across the same range, indicating that the treated steel retains much higher stress before permanent deformation. The strength improvements come at the expense of ductility: elongation to failure decreased from 18% (S1) to 10% (S4). This inverse relationship between strength and ductility is expected, as the harder martensitic structure is less able to accommodate plastic strain. Similarly, impact toughness as measured by Charpy impact energy dropped from 80 J in the untreated sample to 35 J after 6 cycles. The reduction in impact energy (~56% decrease) signifies increased brittleness due to the high hardness, consistent with the presence of martensite which is an inherently tougher yet more brittle phase than ferrite. These trends underscore the classic trade-off in materials science: enhancing strength and hardness through microstructure refinement typically reduces ductility and toughness.

Table 1. Mechanical properties of plain carbon steel as a function of cyclic heat treatment cycles.

Sample	**CHT Cycles**	**Hardness (HV)**	**UTS (MPa)**	**Yield Strength (MPa)**	**Elongation (%)**	**Charpy Impact Energy (J)**
S1 (Base)	0 (As-rec.)	220	680	320	18	80
S2	2	400	1020	480	14	65
S3	4	520	1280	610	12	50
S4	6	640	1540	750	10	35

Beyond tensile properties, the flexural strength and stiffness of the steel were also improved by CHT. In three-point bending tests, the flexural strength (maximum stress at fracture) increased from approximately 550 MPa (S1) to 1120 MPa (S4), roughly a 104% gain. The tensile modulus showed a modest increase from ~190 GPa to 235 GPa, indicating a slightly stiffer material after treatment (likely due to the higher volume fraction of rigid martensite and the elimination of micro-voids). Additionally, density measurements revealed a small increase in density from 7.75 to 7.92 g/cm^3 after 6 cycles, corresponding to a reduction in porosity and more compact microstructure (void fraction dropped from ~4.5% to 0.9% as internal microvoids were closed). These subtle changes support the observation that CHT produces a more homogeneous and consolidated microstructure, which can carry load more effectively.

Phase Transformations and Strengthening Mechanisms

The substantial improvements in hardness and strength can be directly attributed to the microstructural transformations induced by cyclic heat treatment. The initial ferrite-pearlite structure offers limited strength – ferrite is soft and pearlite, while harder, is present in colonies that are relatively coarse. Upon CHT, a large fraction of the ferrite is transformed into martensite (a supersaturated solid solution of carbon in iron) and bainite (a fine non-lamellar mixture of ferrite and cementite). Martensite is a very hard phase due to its distorted tetragonal lattice and high dislocation density, so its formation is the primary reason for the jump in hardness from 220 HV to 640 HV. The Hall–Petch effect also plays a role: the grain refinement (reduction of prior austenite grain size from ~12.5 µm to ~5 µm) means more grain boundaries are present to impede dislocation motion, thereby strengthening the steel. This grain-boundary strengthening complements the transformation hardening. Furthermore, TEM images revealed that with each cycle, cementite (Fe₃C) in the pearlite broke down into smaller particles which eventually became spheroidized nano-particles (~75 nm) dispersed in the martensitic matrix. These nano-sized carbides act as pinning points that block dislocation movement (precipitation strengthening) and also contribute to hardness. The increase in yield strength from 320 MPa to 750 MPa is particularly linked to the presence of these finely dispersed carbides and the high dislocation density of tempered martensite. The overall result is a steel that can resist plastic deformation much better – hence the much higher yield and tensile strengths. However, the same structural changes that increase strength also reduce ductility. Martensite, while strong, is less able to undergo plastic strain; it typically fractures at lower strains compared to ferrite. The drop in elongation from 18% to 10% and in impact energy from 80 J to 35 J is a consequence of the steel becoming more brittle due to a higher martensite content. In essence, the material trades off the ability to deform in a ductile manner for higher load-bearing capacity. In engineering terms, this may be acceptable or even desirable for applications where strength and wear resistance are prioritized over toughness. It is worth noting that the 6-cycle sample, while less tough than the base steel, still has some bainitic phase (as indicated by XRD and SEM), which can impart a bit of toughness compared to fully martensitic structure. Bainite has a feathery structure that is slightly more accommodating than plate martensite, which might explain why the impact energy, though lower, is not zero.

The flexural strength's doubling can be explained by the same factors: a finer microstructure with fewer flaws can sustain higher bending stresses. Flexural tests are sensitive to the extremes of the material (surface and internal flaws). The reduction in porosity (voids closing during CHT) likely contributed to the higher and more reliable bending strength, as there were fewer initiation sites for cracks when the sample was bent. The slight increase in Young's modulus (from 190 to 235 GPa) is consistent with the removal of softer constituents (ferrite) and the predominance of a phase (martensite) that has a slightly higher elastic modulus. This indicates the steel became slightly stiffer in elastic deformation, although the change is not very large (within ~20%).

Overall, the mechanical property changes observed – higher hardness and strength, lower ductility – are fully consistent with the microstructural evolution from a ductile phase mixture to a high-strength martensitic structure. The cyclic nature of the heat treatment allowed reaching a very high strength level (1540 MPa UTS, which is comparable to some low-alloy quenched & tempered steels) without introducing catastrophic quench cracks, since air cooling is gentler than water quenching. It demonstrates that by appropriate cycling, one can obtain a steel that in the as-treated condition has strength on par with more alloyed steels (e.g., the UTS achieved here is similar to that reported for certain alloy carburized steels). The key is that each thermal cycle partially transforms and tempers the microstructure, gradually building up a network of fine martensite and carbides. This also implies there is likely an upper limit or optimum number of cycles; beyond a certain point, additional cycles may yield diminishing returns or even coarsen the microstructure due to over-tempering. In our study, 6 cycles produced the best combination of highest strength/hardness, albeit with lowest toughness. Fewer cycles (2–4) still gave substantial improvements but with slightly better ductility, so depending on application requirements, one might choose an intermediate cycle count to balance properties. For instance, 4 cycles (S3) resulted in ~1280 MPa UTS and 12% elongation, which might be a more balanced profile for structural use than 1540 MPa and 10% elongation at 6 cycles.

Discussion

This study demonstrates that cyclic heat treatment is a viable and effective method to significantly enhance the mechanical performance of plain carbon steel through microstructural refinement. The multiple austenitization cycles promote more thorough transformation of the microstructure than a single treatment. After 6 cycles, the steel's hardness (640 HV) and tensile strength (1540 MPa) are extraordinarily high for a plain carbon steel, approaching values typical of low-alloy high-strength steels. Achieving such properties without adding alloying elements is notable. The improvement can be attributed to several strengthening mechanisms working in concert: phase transformation strengthening (formation of martensite/bainite), grain boundary strengthening (grain refinement), and precipitation strengthening (nano-cementite). In essence, CHT is refining the microstructure to an ultrafine level that would typically require more sophisticated processes (like thermo-mechanical processing or severe cold work plus annealing) to achieve.

One particularly interesting aspect is the formation of nano-sized carbides in the matrix. In conventional quench & temper treatments, one tempers martensite to precipitate fine carbides and restore some ductility. In the cyclic treatment here, each re-austenitization followed by air cooling likely dissolves and re-precipitates carbides, leading to a progressive spheroidization and refinement (as evidenced by TEM). By the final cycle, the microstructure is akin to tempered martensite with fine carbides, which is an optimal structure for high strength. The presence of ~75 nm cementite particles in S4 is significant – such particles inhibit dislocation motion effectively but are small enough not to act as major crack initiation sites themselves. This helps maintain some toughness.

The reduction in ductility and toughness, while expected, means that for applications requiring impact resistance or significant plastic deformation, there is a trade-off to consider. Components made from the 6-cycle treated steel would need to be used in situations where high strength is needed but large deformations are not anticipated (e.g., wear-resistant parts, static high-load parts). If some ductility is required, using fewer cycles (e.g., 2–4 cycles) might be prudent. Indeed, the literature suggests that "over-processing" can reverse some benefits; Mishra *et al.* found an optimal cycle count where beyond that, strength plateaued or even dropped slightly due to tempering effects or retained austenite stabilization. In our results, we did not observe a drop at 6 cycles, but it is plausible that going further (say 8 or 10 cycles) could start to coarsen carbides and reduce hardness. Thus, an optimal cycle count should be determined based on desired properties.

It is also worth comparing CHT to other strengthening methods for carbon steel. Traditional quench and temper can produce similar hardness and strength, but often at the cost of more severe quenches and the need for careful tempering to avoid brittleness. CHT using air cooling is gentler; it might introduce less thermal stress each cycle. While we did not explicitly measure residual stresses, air-cooled samples typically have lower quench stresses than water-quenched ones. The cyclic approach could therefore reduce the risk of distortion in heat-treated parts, which is an advantage in industrial settings where dimensional stability is important. Additionally, the process is relatively simple (it uses standard furnaces, no special atmospheres or quenchants beyond air). The main trade-off is the longer processing time (multiple cycles take more time/energy than a single heat treatment). Therefore, whether CHT is industrially attractive might depend on energy costs versus the performance gain. For high-volume production, doing 4–6 cycles might be too time-consuming; however, for critical components or when using a continuous furnace, it might be feasible.

The improvements in flexural strength and the observed densification (increase in density, reduction in porosity) indicate another benefit of CHT: it can help eliminate internal defects. During repeated heating and cooling, micro-voids can shrink or close, and any precipitates or second-phase particles (like iron sulfides or oxides) might redistribute more evenly. The density increase from 7.75 to 7.92 g/cm³ is small (~2%) but shows the material became slightly more compact. In practical terms, this could mean improved fatigue life as well, since fewer internal defects mean fewer crack initiation sites. Although not directly measured in this study, it is reasonable to expect the high-cycle fatigue strength of the treated steel would be higher than that of the base steel, owing to the finer grain size and absence of large pearlite colonies (pearlite/ferrite interfaces can initiate fatigue cracks).

One must consider, however, the reduction in impact toughness. For structural applications requiring toughness (e.g., pressure vessels, bridges in cold climates), the drop to 35 J may be unacceptable, as it indicates a transition towards brittle behavior. If toughness is crucial, intermediate treatments or a lower cycle count might be used as a compromise. Alternatively, a two-stage treatment (a few cycles for strength, then a light tempering to restore some toughness) could be explored in future work. The challenge is to maintain the fine microstructure while relieving stresses to improve toughness.

In summary, the CHT process effectively leverages known metallurgical mechanisms (phase transformation and refinement) in a repetitive way to push plain carbon steel into a higher performance regime. It validates CHT as a practical technique: even without alloying, we achieved a material that in its 6-cycle state has hardness and strength comparable to more expensive alloy steels or through-hardened medium-carbon steels. This could have implications in industries like automotive or agricultural machinery, where plain carbon steels are used extensively. By applying CHT, parts like plowshares, gears, or shafts could potentially have longer service life due to higher strength and wear resistance, using the same base steel. The cost comes as additional furnace time rather than expensive alloy additions.

Conclusion

Through the application of cyclic heat treatment, we have demonstrated substantial improvement of the mechanical properties of plain carbon steel by microstructural refinement. Key findings from this research are:

- **Hardness and Strength:** Repeated austenitization and air-cooling cycles converted the ferrite–pearlite microstructure into a fine martensitic–bainitic structure, yielding a remarkable increase in hardness (from 220 HV to 640 HV) and ultimate tensile strength (680 MPa to 1540 MPa). These gains (roughly +201% in hardness and +126% in UTS) highlight CHT's efficacy in strengthening plain carbon steel to levels typical of quenched and tempered alloy steels.
- **Microstructural Refinement:** Each heat treatment cycle progressively refined the grain structure and phase distribution. The original coarse ferrite and pearlite were largely eliminated in favor of lath martensite and fine bainite by 4–6 cycles. Prior-austenite grain size was roughly halved (down to ~5 µm), and nano-scale cementite precipitates (~50–100 nm) were uniformly distributed in the matrix after multiple cycles. XRD confirmed the reduction of soft ferrite/pearlite phases and the predominance of martensitic phases in heavily cycled samples.
- **Trade-Off in Ductility:** The improvements in strength came with reduced ductility and toughness. Total elongation dropped from 18% to 10%, and Charpy impact energy from 80 J to 35 J, from 0 to 6 cycles. This is attributed to the high martensite content and associated higher brittleness. The data emphasize the need to balance the number of cycles to achieve desired properties – for instance, 2–4 cycles yield somewhat lower strength but better ductility than 6 cycles.
- **Flexural Strength and Modulus:** The flexural (bending) strength doubled (≈550 MPa to 1120 MPa) with cycling, and the Young's modulus increased modestly (≈190 to 235 GPa). This suggests an overall increase in rigidity and load-bearing capacity. The reduction of internal voids (porosity ~4.5% to 0.9%)likely contributed to more efficient stress transfer in the material.
- **Mechanisms:** The enhanced properties are the result of combined mechanisms: martensitic transformation (providing a harder phase), grain refinement (Hall–Petch strengthening), and precipitation of fine carbides (impeding dislocations). The cyclic nature allowed repeated refinement and tempering, producing a uniformly hardened structure without the need for extreme quench rates that can introduce cracking.

In conclusion, cyclic heat treatment proves to be a powerful tool for improving plain carbon steel. By carefully selecting the number of cycles, one can tailor the strength–ductility balance to meet specific application requirements. For applications where maximum hardness and strength are desired (e.g., wear parts), a higher cycle count (6 or more) is beneficial. For applications needing some toughness, a lower cycle count can be used to achieve a compromise. This strategy offers a cost-effective alternative to alloying: it uses time and controlled thermal cycling to attain mechanical properties that otherwise might require more expensive alloy steels. Future work could explore the effect of cycle parameters (temperature, cooling rate) and post-cycle tempers on toughness. Additionally, investigating the fatigue performance of cyclically heat-treated steel would be valuable, since a refined microstructure often improves fatigue life. Overall, this study contributes to the understanding that plain carbon steel, through innovative heat treatment schedules, can reach higher echelons of performance, broadening its utility in advanced engineering applications.

References

1. Alkhawaldeh, A. A., & Alrousan, R. Z. (2023). Improving cyclic response of heat-damaged non-ductile RC joints using CFRP hybrid systems. *Construction and Building Materials*, *377*, 131150. https://doi.org/10.1016/j.conbuildmat.2023.131150
2. Gao, B., Wang, L., Liu, Y., Liu, J., Xiao, L., Sui, Y., ... & Zhou, H. (2023). Achieving ultrahigh strength by tuning the hierarchical structure of low-carbon martensitic steel. *Materials Science and Engineering: A*, *881*, 145370. https://doi.org/10.1016/j.msea.2023.145370
3. Singh, J., & Nath, S. K. (2022). Microstructural characterization and investigation of slurry erosion performance of cyclically heat treated martensite steel. *Engineering Failure Analysis*, *131*, 105833. https://doi.org/10.1016/j.engfailanal.2021.105833
4. Xia, P., Vercruysse, F., Celada-Casero, C., Verleysen, P., Petrov, R. H., Sabirov, I., ... & Lara, A. (2022). Effect of alloying and microstructure on formability of advanced high-strength steels processed via quenching and partitioning. *Materials Science and Engineering: A*, *831*, 142217. https://doi.org/10.1016/j.msea.2021.142217
5. Perka, A. K., John, M., Kuruveri, U. B., & Menezes, P. L. (2022). Advanced high-strength steels for automotive applications: Arc and laser welding process, properties, and challenges. *Metals*, *12*(6), 1051. https://doi.org/10.3390/met12061051
6. Liu, G., Zhang, M., Feng, Y., Cao, K., Li, S., & Wang, Y. (2022). Influence of warm rolling temperature on multi-scale lamellar structure and mechanical properties of medium carbon steel. *Journal of Materials Research and Technology*, *18*, 3739-3750. https://doi.org/10.1016/j.jmrt.2022.04.047

7. Penha, R. N., & Marins, Y. F. S. (2022). Quenching and partitioning heat treatment: the third generation of advanced high-strength steel. *Research, Society and Development*, *11*(10), e346111031903-e346111031903. https://doi.org/10.33448/rsd-v11i10.31903
8. Chabok, A., Cao, H., van der Aa, E., & Pei, Y. (2022). New insights into the fracture behavior of advanced high strength steel resistance spot welds. *Journal of Materials Processing Technology*, *301*, 117433. https://doi.org/10.1016/j.jmatprotec.2021.117433
9. Branco, R., Martins, R. F., Correia, J. A., Marciniak, Z., Macek, W., & Jesus, J. (2022). On the use of the cumulative strain energy density for fatigue life assessment in advanced high-strength steels. *International Journal of Fatigue*, *164*, 107121. https://doi.org/10.1016/j.ijfatigue.2022.107121
10. Lu, Y., Wang, G., Zhang, M., Li, R., & Zhang, H. (2022). Microstructures, heat treatments and mechanical properties of AerMet100 steel fabricated by hybrid directed energy deposition. *Additive Manufacturing*, *56*, 102885. https://doi.org/10.1016/j.addma.2022.102885
11. Patra, A. K., Athreya, C. N., Mandal, S., Kumar, K. H., & Sarma, V. S. (2021). High strength-high ductility medium Mn steel obtained through CALPHAD based alloy design and thermomechanical processing. *Materials Science and Engineering: A*, *810*, 140756. https://doi.org/10.1016/j.msea.2021.140756
12. Li, K., Klecka, M. A., Chen, S., & Xiong, W. (2021). Wire-arc additive manufacturing and post-heat treatment optimization on microstructure and mechanical properties of Grade 91 steel. *Additive Manufacturing*, *37*, 101734. https://doi.org/10.1016/j.addma.2020.101734
13. Soleimani, M., Mirzadeh, H., & Dehghanian, C. (2021). Effects of spheroidization heat treatment and intercritical annealing on mechanical properties and corrosion resistance of medium carbon dual phase steel. *Materials Chemistry and Physics*, *257*, 123721. https://doi.org/10.1016/j.matchemphys.2020.123721
14. Misra, S. K., & Nath, S. K. (2021). Development of dual-phase steels from plain carbon sheet steels. *International Journal of Materials Research*, *89*(11), 779-782. https://doi.org/10.3139/ijmr-1998-0148
15. Kandpal, B. C., Gupta, D. K., Kumar, A., Jaisal, A. K., Ranjan, A. K., Srivastava, A., & Chaudhary, P. (2021). Effect of heat treatment on properties and microstructure of steels. *Materials today: proceedings*, *44*, 199-205. https://doi.org/10.1016/j.matpr.2020.08.556
16. Nasiri, Z., Ghaemifar, S., Naghizadeh, M., & Mirzadeh, H. (2021). Thermal mechanisms of grain refinement in steels: a review. *Metals and Materials International*, *27*, 2078-2094. https://link.springer.com/article/10.1007/s12540-020-00700-1
17. Nemani, A. V., Ghaffari, M., Salahi, S., & Nasiri, A. (2021). Effects of post-printing heat treatment on the microstructure and mechanical properties of a wire arc additive manufactured 420 martensitic stainless steel part. *Materials Science and Engineering: A*, *813*, 141167. https://doi.org/10.1016/j.msea.2021.141167
18. Carpio, M., Calvo, J., García, O., Pedraza, J. P., & Cabrera, J. M. (2021). Heat treatment design for a QP steel: Effect of partitioning temperature. *Metals*, *11*(7), 1136. https://doi.org/10.3390/met11071136
19. Mallick, M., Mitra, S. K., Basak, D., Roy, N. K., & Maity, J. (2021). A novel approach of high-voltage low-current electric energy input to synthesise cost-effective ultra-strong ductile material. *Philosophical Magazine*, *101*(5), 555-575. https://doi.org/10.1080/14786435.2020.1849843
20. Podgornik, B., Šinko, M., & Godec, M. (2021). Dependence of the wear resistance of additive-manufactured maraging steel on the build direction and heat treatment. *Additive Manufacturing*, *46*, 102123. https://doi.org/10.1016/j.addma.2021.102123
21. Matlock, D. K., Kang, S., De Moor, E., & Speer, J. G. (2020). Applications of rapid thermal processing to advanced high strength sheet steel developments. *Materials Characterization*, *166*, 110397. https://doi.org/10.1016/j.matchar.2020.110397
22. Singh, J., & Nath, S. K. (2020). Improved slurry erosion resistance of martensitic 13wt.% Cr–4wt.% Ni steel subjected to cyclic heat treatment. *Wear*, *460*, 203476. https://doi.org/10.1016/j.wear.2020.203476
23. Farivar, H., Deepu, M. J., Hans, M., Phanikumar, G., Bleck, W., & Prahl, U. (2019). Influence of post-carburizing heat treatment on the core microstructural evolution and the resulting mechanical properties in case-hardened steel components. *Materials Science and Engineering: A*, *744*, 778-789. https://doi.org/10.1016/j.msea.2018.12.061
24. Saeidi, K., Zapata, D. L., Lofaj, F., Kvetkova, L., Olsen, J., Shen, Z., & Akhtar, F. (2019). Ultra-high strength martensitic 420 stainless steel with high ductility. *Additive Manufacturing*, *29*, 100803. https://doi.org/10.1016/j.addma.2019.100803
25. Badaruddin, M., Wardono, H., Wang, C. J., & Rivai, A. K. (2019). Improvement of low-cycle fatigue resistance in AISI 4140 steel by annealing treatment. *International Journal of Fatigue*, *125*, 406-417. https://doi.org/10.1016/j.ijfatigue.2019.04.020
26. Nouroozi, M., Mirzadeh, H., & Zamani, M. (2018). Effect of microstructural refinement and intercritical annealing time on mechanical properties of high-formability dual phase steel. *Materials Science and Engineering: A*, *736*, 22-26. https://doi.org/10.1016/j.msea.2018.08.088
27. Pandey, C., Mahapatra, M. M., Kumar, P., & Saini, N. (2018). Homogenization of P91 weldments using varying normalizing and tempering treatment. *Materials Science and Engineering: A*, *710*, 86-101. https://doi.org/10.1016/j.msea.2017.10.086

28. Li, S., Xiao, M., Ye, G., Zhao, K., & Yang, M. (2018). Effects of deep cryogenic treatment on microstructural evolution and alloy phases precipitation of a new low carbon martensitic stainless bearing steel during aging. *Materials Science and Engineering: A*, *732*, 167-177. https://doi.org/10.1016/j.msea.2018.07.012
29. Ghosh, A., & Ghosh, M. (2018). Tensile and impact behaviour of thermo mechanically treated and micro-alloyed medium carbon steel bar. *Construction and Building Materials*, *192*, 657-670. https://doi.org/10.1016/j.conbuildmat.2018.10.098
30. Hou, Z., Babu, R. P., Xu, Y., & Wu, D. (2018). Enhanced grain growth behavior of ferritic steel during continuous cyclic annealing. *steel research international*, *89*(11), 1800222. https://doi.org/10.1002/srin.201800222
31. Fatoba, O., & Akid, R. (2018). Uniaxial cyclic elasto-plastic deformation and fatigue failure of API-5L X65 steel under various loading conditions. *Theoretical and Applied Fracture Mechanics*, *94*, 147-159. . https://doi.org/10.1016/j.tafmec.2018.01.015
32. Maleki, E., Unal, O., & Kashyzadeh, K. R. (2018). Effects of conventional, severe, over, and re-shot peening processes on the fatigue behavior of mild carbon steel. *Surface and Coatings Technology*, *344*, 62-74. https://doi.org/10.1016/j.surfcoat.2018.02.081
33. Mishra, S., Mishra, A., Show, B. K., & Maity, J. (2017). Simultaneous enhancement of ductility and strength in AISI 1080 steel through a typical cyclic heat treatment. *Materials Science and Engineering: A*, *688*, 262-271. https://doi.org/10.1016/j.msea.2017.02.003
34. Mishra, A., Mondal, C., & Maity, J. (2017). Effect of Combined Cyclic Heat Treatment on AISI 1080 Steel: Part II-Mechanical Property Evaluation. *steel research international*, *88*(4), 1600215. https://doi.org/10.1002/srin.201600215
35. Melado, A. C., Nishikawa, A. S., Goldenstein, H., Giles, M. A., & Reed, P. A. (2017). Effect of microstructure on fatigue behaviour of advanced high strength ductile cast iron produced by quenching and partitioning process. *International Journal of Fatigue*, *104*, 397-407. https://doi.org/10.1016/j.ijfatigue.2017.07.009
36. Mishra, A., Saha, A., & Maity, J. (2016). Development of high strength ductile eutectoid steel through cyclic heat treatment involving incomplete austenitization followed by forced air cooling. *Materials characterization*, *114*, 277-288. https://doi.org/10.1016/j.matchar.2016.03.001
37. Ding, W., Hedström, P., & Li, Y. (2016). Heat treatment, microstructure and mechanical properties of a C–Mn–Al–P hot dip galvanizing TRIP steel. *Materials Science and Engineering: A*, *674*, 151-157. https://doi.org/10.1016/j.msea.2016.07.119
38. Prabhakaran, S., & Kalainathan, S. (2016). Compound technology of manufacturing and multiple laser peening on microstructure and fatigue life of dual-phase spring steel. *Materials Science and Engineering: A*, *674*, 634-645. https://doi.org/10.1016/j.msea.2016.08.031
39. Gao, G., Zhang, B., Cheng, C., Zhao, P., Zhang, H., & Bai, B. (2016). Very high cycle fatigue behaviors of bainite/martensite multiphase steel treated by quenching-partitioning-tempering process. *International Journal of Fatigue*, *92*, 203-210. https://doi.org/10.1016/j.ijfatigue.2016.06.025
40. Bach, J., Möller, J. J., Göken, M., Bitzek, E., & Höppel, H. W. (2016). On the transition from plastic deformation to crack initiation in the high-and very high-cycle fatigue regimes in plain carbon steels. *International Journal of Fatigue*, *93*, 281-291. https://doi.org/10.1016/j.ijfatigue.2016.04.003
41. Mishra, A., & Maity, J. (2015). Structure–property correlation of AISI 1080 steel subjected to cyclic quenching treatment. *Materials Science and Engineering: A*, *646*, 169-181. https://doi.org/10.1016/j.msea.2015.08.018
42. Kumar, A., Sharma, A., & Goel, S. K. (2015). Effect of heat treatment on microstructure, mechanical properties and erosion resistance of cast 23-8-N nitronic steel. *Materials Science and Engineering: A*, *637*, 56-62. https://doi.org/10.1016/j.msea.2015.04.031
43. Khorrami, M. S., Mostafaei, M. A., Pouraliakbar, H., & Kokabi, A. H. (2014). Study on microstructure and mechanical characteristics of low-carbon steel and ferritic stainless steel joints. *Materials Science and Engineering: A*, *608*, 35-45. https://doi.org/10.1016/j.msea.2014.04.065
44. De Knijf, D., Petrov, R., Föjer, C., & Kestens, L. A. (2014). Effect of fresh martensite on the stability of retained austenite in quenching and partitioning steel. *Materials Science and Engineering: A*, *615*, 107-115. https://doi.org/10.1016/j.msea.2014.07.054
45. Saeidi, N., Ashrafizadeh, F., & Niroumand, B. (2014). Development of a new ultrafine grained dual phase steel and examination of the effect of grain size on tensile deformation behavior. *Materials Science and Engineering: A*, *599*, 145-149. https://doi.org/10.1016/j.msea.2014.01.053