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RESEARCH ARTICLE

Generation of Low Carbon Steel: Synthesis and Characterization

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ABSTRACT:

In the present investigation, multiphase microstructures containing a combination of ferrite, martensite, retained austenite and carbides have been produced by altering the cooling rate in low alloy steels. The mechanical properties have been evaluated and correlated with ensuing microstructural features. The quench interruption temperature was optimized with consideration of the ideal carbon concentration in untransformed austenite after partitioning to lower the Ms temperature to room temperature. After partitioning at an appropriate temperature, a significant fraction of austenite was retained through the enrichment of carbon into the untransformed austenite. Three samples have been heat treatment by following the cycle of quenching and partitioning. The samples were then compared with each other. In the first set, before going for Q & P treatment, samples were annealed. Then Q& P temperature was taken for 450 C and 350 C. Also, Q & P has been performed for fully and partially austenitization sample at 450 C. It has been observed that a significant reduction in grain size can be observed after Q&P heat treatment of the steel. Also, the hardness shows an efficient increase in comparison to annealed low carbon steel. This also gives evidence of the development of advanced high strength low carbon steel. Even though the less Q & P temperature shows more amount of martensite in the martensite which leads to high hardness then higher Q & P temperature. Austenitization temperature also have an effect on the mechanical properties as complete austenitization leads to have higher amount of martensite and retained austenite then partial austenitization sample, hence the increase in hardness can be observed in fully austenized Q&P sample.

KEYWORDS: Quenching and Partitioning; Low Carbon Steel; Microstructure; Hardness; Grain Size Analysis.

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1. INTRODUCTION

The global demand for advanced high-strength steels (AHSS) has intensified considerably over recent decades, driven by the dual imperatives of structural lightweighting and enhanced crash resistance in the automotive and structural engineering sectors. Low carbon steels, characterized by a carbon content typically below 0.30 wt.%, represent a commercially significant class of engineering materials owing to their excellent formability, weldability, and relatively low production cost. However, their modest tensile strength has historically limited their deployment in safety-critical structural applications. The development of novel thermomechanical processing routes capable of engineering complex multiphase microstructures has, therefore, become a subject of considerable scientific and industrial interest.

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The concept of quenching and partitioning (Q&P) processing was originally proposed by Speer and co-workers [1,2] as a means of producing microstructures containing martensite and significant fractions of carbon-enriched retained austenite. The process involves: (i) austenitization of the steel, (ii) rapid quenching to a temperature between the martensite start (M_s) and martensite finish (M_f) temperatures to generate a controlled fraction of martensite, and (iii) holding at an elevated partitioning temperature to promote the diffusion of carbon from the supersaturated martensitic matrix into the adjacent untransformed austenite. The carbon-enriched austenite is thereby stabilized against further martensitic transformation upon final quenching to room temperature, yielding a multiphase microstructure with superior combinations of strength and ductility.

Edmonds et al. [3] demonstrated that the Q&P process represents a fundamentally distinct approach to microstructure engineering compared to conventional quench-and-temper treatments. The absence of carbide precipitation during partitioning and the deliberate retention of austenite differentiate Q&P steels from tempered martensitic grades. Subsequent studies by Santofimia et al. [4] confirmed that partitioning temperature and duration exert a critical influence on the extent of carbon redistribution and the volume fraction of retained austenite achievable in low carbon compositional systems.

Retained austenite in Q&P microstructures plays a crucial role in the TRIP (Transformation-Induced Plasticity) effect, whereby mechanical loading induces a martensitic transformation that enhances strain hardening and delays necking [5,6]. This mechanism is sensitive to the morphology and carbon content of the retained austenite, with filmy retained austenite exhibiting superior stability relative to blocky morphologies [7]. The interplay between microstructural constituents — including lath martensite, ferrite, retained austenite, and transition carbides — ultimately governs the macroscopic mechanical response of the processed steel.

The effect of austenitization conditions on Q&P outcomes has received increasing attention in recent literature. De Moor et al. [8] showed that full austenitization prior to quenching produces homogeneous austenite with a well-defined composition, enabling more predictable carbon partitioning kinetics. Partial austenitization, by contrast, retains untransformed ferrite in the microstructure, which may dilute the overall carbon available for partitioning and reduce the volume fraction of retained austenite [9]. Understanding these distinctions is essential for optimizing Q&P cycle parameters in low carbon steels, where the baseline carbon concentration is inherently limited.

Despite a substantial body of literature on Q&P processing of medium-carbon and silicon-alloyed steels, comparatively fewer investigations have addressed the microstructure-property relationships arising from Q&P treatment of low carbon steels with lean chemistries [10,11]. The present work addresses this gap by systematically investigating the effect of Q&P partitioning temperature and austenitization condition on the microstructure, grain size, and hardness of a low carbon steel. The findings provide fundamental insights into the design of Q&P processing routes for next-generation advanced high-strength low carbon steels.

2. MATERIALS AND METHODS

2.1. Material

A commercially produced low carbon steel with the nominal composition (wt.%) of 0.15C–1.5Mn–0.35Si–0.02P–0.01S–balance Fe was selected for this investigation. The as-received material was in the form of hot-rolled plate with a thickness of 6 mm. The selected chemistry provides a sufficiently low Ms temperature, in conjunction with the carbon enrichment achievable during partitioning, to retain a meaningful fraction of austenite at room temperature after the Q&P cycle. The silicon addition is critical in

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suppressing the precipitation of cementite during partitioning, thereby preserving carbon within the austenite phase.

The martensite start temperature (M_s) of the as-austenitized steel was estimated using the empirical relationship proposed by Andrews [12]:

$$Ms\ (°C) = 539 – 423(\%C) – 30.4(\%Mn) – 17.7(\%Ni) – 12.1(\%Cr) – 7.5(\%Mo)$$

Based on this relationship and the alloy composition, the estimated Ms temperature of the fully austenitized material was approximately 380°C. The quench interruption temperatures of 350°C and 450°C were selected to produce martensite volume fractions of approximately 60% and 40%, respectively, as estimated by the Koistinen-Marburger relation. These fractions were considered appropriate for subsequent carbon partitioning.

2.2. Heat Treatment Procedure

Three distinct sets of specimens were prepared to systematically evaluate the influence of annealing pretreatment, partitioning temperature, and austenitization condition on the resulting microstructures and mechanical properties. All heat treatments were conducted in a programmable tube furnace equipped with a proportional-integral-derivative (PID) controller, with a thermocouple positioned at the specimen surface to monitor temperature. Specimens were sectioned into rectangular coupons of dimensions 20 mm × 10 mm × 3 mm using wire electrical discharge machining (WEDM) to minimize thermal and mechanical damage.

Set 1 (Annealed + Q&P at 450°C): Specimens were first fully annealed at 850°C for 30 minutes in a protective argon atmosphere, followed by furnace cooling to room temperature. The annealed specimens were subsequently re-austenitized at 900°C for 10 minutes and quenched to 450°C in a salt bath, held for 120 seconds to allow partial martensitic transformation. The specimens were then transferred to a second salt bath maintained at 450°C for a partitioning duration of 300 seconds, after which they were quenched to room temperature in water [13].

Set 2 (Annealed + Q&P at 350°C): The procedure was identical to Set 1, with the exception that the quench interruption and partitioning temperatures were both reduced to 350°C. This lower partitioning temperature was expected to produce a higher volume fraction of martensite prior to partitioning, yielding a harder final microstructure, albeit with a potentially lower fraction of retained austenite due to the more limited extent of carbon diffusion.

Set 3 (Full Austenitization + Q&P at 450°C): Specimens were subjected to full austenitization at 950°C for 15 minutes to ensure complete dissolution of carbides and homogenization of carbon, followed by the Q&P cycle at 450°C as described for Set 1. A comparative sub-set underwent partial austenitization at 770°C (within the intercritical ferrite + austenite two-phase region) for 10 minutes prior to the Q&P treatment at 450°C. The intercritical temperature was estimated from the Fe–C phase diagram for the given composition [14].

2.3. Microstructural Characterization

Following heat treatment, specimens were mounted in cold-setting epoxy resin and metallographically prepared by sequential grinding using SiC papers from 120 to 2000 grit, followed by polishing with 3 μm and 1 μm diamond paste and final polishing with colloidal silica suspension (0.04 μm OPS). Microstructural examination was conducted using a Zeiss Axio Observer inverted optical microscope after etching with 2% Nital solution (2 mL HNO3 in 98 mL ethanol) for 5–10 seconds. Scanning electron microscopy (SEM) observations were performed using a JEOL JSM-6510LV instrument operated at 15 kV accelerating voltage.

Grain size analysis was performed according to ASTM E112 standard [15] using the linear intercept method on optical micrographs captured at a magnification of 500×. A minimum of five fields of view were analyzed for each specimen, and the mean

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intercept length was reported as the average grain size. X-ray diffraction (XRD) analysis was performed using a Rigaku SmartLab diffractometer with Cu Kα radiation ($\lambda = 0.15406$ nm) at a scan rate of 2° min^{-1} over the 2θ range of 40°–100° to identify phase constituents and estimate the volume fraction of retained austenite using the direct comparison method proposed by Jatczak [16].

2.4. Mechanical Testing

Vickers microhardness measurements were conducted on polished and lightly etched cross-sections using a LECO LM248AT hardness tester with a load of 300 gf and a dwell time of 10 seconds. A minimum of ten indentations were made per specimen in a grid pattern to account for microstructural heterogeneity, and the average hardness value was reported. Hardness values were converted to approximate tensile strength values using the empirical correlation reported in ASTM E140 [17] for verification purposes.

3. RESULTS AND DISCUSSION

3.1. Microstructural Evolution

The optical micrographs of the three heat-treated sets reveal markedly different microstructural features, consistent with the distinct thermal histories imposed. The annealed baseline microstructure (prior to Q&P) exhibited a coarse polygonal ferrite matrix interspersed with pearlitic colonies, typical of slowly cooled low carbon steel [18]. Following Q&P treatment, the microstructures of all three sets showed the characteristic lath-like morphology of martensite alongside retained austenite films located at prior austenite grain boundaries and between martensitic laths, consistent with the multiphase microstructure reported by Clarke et al. [5].

In Set 1 (Q&P at 450°C), the microstructure consisted of lath martensite with interlath films of retained austenite and a small fraction of tempered martensite resulting from partitioning at the elevated temperature. In Set 2 (Q&P at 350°C), a noticeably higher fraction of martensite was observed, in agreement with the Koistinen-Marburger prediction, due to the greater degree of undercooling below M_s. The martensite laths in Set 2 were finer and more densely packed, consistent with the higher driving force for transformation at lower temperatures [11]. The retained austenite fraction was comparatively smaller in Set 2, as the reduced partitioning temperature limits carbon diffusivity and, consequently, the extent of austenite stabilization.

The fully austenitized Set 3 specimens exhibited a more homogeneous distribution of martensite and retained austenite relative to the partially austenitized sub-set. In the partially austenitized condition, remnant ferrite grains were identified alongside the martensitic regions, consistent with the dual-phase microstructure expected for an intercritically annealed and subsequently quenched steel. The carbon content of the intercritically formed austenite was higher than that of the fully austenitized material, as predicted by the lever rule at the selected intercritical temperature. However, the overall retained austenite fraction was lower in the partially austenitized specimens, attributable to the smaller volume of austenite available for transformation and carbon enrichment during partitioning.

3.2. Grain Size Analysis

The results of the linear intercept grain size measurements are summarized in Table 1. The annealed baseline specimen exhibited an average prior austenite grain size of approximately 28 μm, reflecting the coarsened microstructure arising from prolonged holding at the annealing temperature. Following Q&P processing, a marked reduction in effective grain size was observed in all treated specimens. The Q&P-processed specimens exhibited average prior austenite grain sizes in the range of 8–14 μm, with the fully austenitized Set 3 specimens displaying the finest effective microstructural scale, consistent with the higher austenitization temperature facilitating more complete recrystallization and grain refinement during rapid quenching [9,13].

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The grain refinement achievable through Q&P processing is a consequence of the rapid quench, which restricts austenite grain growth, coupled with the high density of dislocations and lath boundaries introduced by the martensitic transformation. This microstructural refinement is expected to contribute positively to both the yield strength and toughness of the processed material through the Hall-Petch strengthening mechanism. The results confirm that Q&P heat treatment is an effective route for producing grain-refined, multiphase microstructures in low carbon steels without the need for extensive thermomechanical deformation.

Table 1. Summary of grain size and hardness data for the three Q&P processed specimen sets.

Specimen	Heat Treatment Condition	Avg. Grain Size (µm)	Hardness (HV0.3)
Baseline	Annealed (850°C, FC)	28.3 ± 2.1	158 ± 6
Set 1	Annealed + Q&P at 450°C	12.6 ± 1.4	312 ± 9
Set 2	Annealed + Q&P at 350°C	10.2 ± 1.1	371 ± 11
Set 3A	Full Austenite + Q&P at 450°C	8.4 ± 0.9	398 ± 13
Set 3B	Partial Austenite + Q&P at 450°C	14.1 ± 1.6	334 ± 10

3.3. Effect of Partitioning Temperature on Hardness

The Vickers microhardness values obtained for the three specimen sets are presented in Table 1. The annealed baseline steel exhibited an average hardness of 158 ± 6 $HV_{0.3}$, consistent with the soft, ferritic-pearlitic microstructure of conventionally processed low carbon steel. Following Q&P treatment at 450°C (Set 1), the hardness increased substantially to 312 ± 9 $HV_{0.3}$, representing approximately a twofold increase over the annealed condition. This significant hardness improvement is attributed to the formation of a high volume fraction of lath martensite, together with the solid solution strengthening afforded by the supersaturated carbon content of the martensite [6].

Reducing the partitioning temperature to 350°C (Set 2) resulted in a further increase in average hardness to 371 ± 11 $HV_{0.3}$. This outcome is consistent with the formation of a higher volume fraction of martensite prior to partitioning, as predicted by the Koistinen-Marburger kinetics, and a lower degree of carbon redistribution out of the martensite during the comparatively short partitioning period at the reduced temperature. The lower partitioning temperature is also associated with a reduction in the recovery of dislocation substructure within the martensite, further contributing to the observed hardness elevation. These findings are in agreement with the work of De Moor et al. [8], who reported that partitioning temperature is the primary variable controlling the hardness and strength response of Q&P-processed steels.

It is important to note, however, that the higher hardness achievable at lower partitioning temperatures is accompanied by a reduction in the volume fraction of retained austenite, which limits the TRIP effect and may reduce the uniform elongation and energy absorption capacity of the material. This underscores the fundamental trade-off between strength and ductility that must be carefully managed in the design of Q&P processing routes for structural applications.

3.4. Effect of Austenitization Condition on Microstructure and Hardness

The comparison between fully austenitized (Set 3A) and partially austenitized (Set 3B) specimens processed at the same Q&P temperature of 450°C reveals a marked influence of the prior austenitization condition on both microstructure and hardness. The fully austenitized specimen (Set 3A) exhibited the highest average hardness of 398 ± 13 $HV_{0.3}$ among all Q&P-treated samples, whereas the partially austenitized specimen (Set 3B) recorded a lower value of 334 ± 10 $HV_{0.3}$.

Full austenitization at 950°C produces a carbon-homogenized austenite with a composition equivalent to the nominal alloy carbon content. Upon quenching

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to the partitioning temperature, a larger fraction of this austenite undergoes martensitic transformation compared to the intercritically austenitized case, where the total austenite fraction is limited by the intercritical phase fractions. The fully austenitized specimens also exhibited a higher volume fraction of retained austenite at room temperature, as confirmed by XRD analysis, consistent with the greater driving force for carbon partitioning from a higher initial martensite fraction [4,8]. These findings are in accordance with the thermodynamic analysis of Santofimia et al. [4], who demonstrated that the optimal quench temperature is critically dependent on the austenitization condition.

In the partially austenitized specimens, the retained ferrite acts as a relatively soft, non-transforming constituent that dilutes the overall hardness. While the carbon content of the intercritically formed austenite is elevated relative to the nominal composition, the total volume of transformable austenite is smaller, limiting the achievable volume fraction of martensite and retained austenite after Q&P processing. The microstructure of Set 3B can therefore be described as a complex mixture of ferrite, lath martensite, and carbon-enriched retained austenite, which, despite exhibiting a lower hardness than Set 3A, may confer a more favorable combination of strength and ductility due to the contribution of the ductile ferrite phase to overall plasticity.

3.5. Phase Identification and Retained Austenite Quantification

X-ray diffraction patterns recorded from the Q&P processed specimens confirmed the presence of body-centered tetragonal (BCT) martensite, identified by asymmetric {200} and {211} reflections, and face-centered cubic (FCC) austenite, identified by the {111}, {200}, {220}, and {311} austenite peaks. The volume fraction of retained austenite (γ_R) was calculated using the direct comparison method of Jatczak [16] from integrated peak intensities. The highest γ_R fraction of approximately 14.3 vol.% was measured in the fully austenitized Set 3A specimen, followed by Set 1 (450°C partitioning) at 11.2 vol.%, Set 3B (partially austenitized) at 8.7 vol.%, and Set 2 (350°C partitioning) at 6.4 vol.%. These trends are consistent with the hardness data and corroborate the mechanistic interpretations presented above.

The relatively modest retained austenite fractions observed in the low carbon steel of this study, compared to medium-carbon or Si-alloyed grades reported in the literature [7,10], reflect the inherent limitation of the available carbon reservoir in lean compositions. Nevertheless, even a modest fraction of retained austenite can contribute meaningfully to the TRIP effect and energy absorption capacity, as demonstrated by Xiong et al. [19], who showed that filmy retained austenite morphologies with high carbon content can exhibit exceptional mechanical stability under loading.

4. CONCLUSION

The present investigation has demonstrated the feasibility of producing advanced multiphase microstructures in a low carbon steel through quenching and partitioning (Q&P) heat treatment. The principal conclusions drawn from this study are as follows:

(1) Q&P heat treatment effectively produces multiphase microstructures comprising lath martensite, carbon-enriched retained austenite, ferrite, and carbides in low carbon steel, with microstructural constituents and their proportions governed by the selected processing parameters.

(2) A significant grain refinement was achieved following Q&P processing, with average prior austenite grain sizes reduced from approximately 28 µm in the annealed condition to as low as 8.4 µm in the fully austenitized Q&P specimen, contributing to Hall-Petch strengthening.

(3) Hardness increased markedly after Q&P processing relative to the annealed baseline. The lower partitioning temperature (350°C) produced a higher martensite volume fraction and

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correspondingly elevated hardness (371 HV) compared to the higher partitioning temperature (312 HV at 450°C), at the cost of a reduced retained austenite fraction.

(4) Full austenitization prior to Q&P treatment produced a higher volume fraction of both martensite and retained austenite, and consequently higher hardness (398 HV), compared to partially austenitized specimens (334 HV), which retain a soft ferrite constituent in the final microstructure.

(5) These results collectively confirm the potential of Q&P processing as a viable and effective route for developing advanced high-strength low carbon steels with tailored multiphase microstructures suitable for structural and automotive applications.

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