Effect of Martensite Distribution on Microscopic Deformation Behavior and Mechanical Properties of Dual-Phase Steel: Postprint

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Abstract

Through process design, industrial 20 steel was subjected to step quenching (SQ) and intercritical annealing (IA) heat treatments, yielding two types of dual-phase steels with similar martensite volume fractions but with martensite distributed discretely and continuously, respectively. The tensile/impact mechanical properties of these steels were characterized; the microscale strain distribution in the dual-phase steels was obtained using the digital image correlation (DIC) method and combined with surface microcrack analysis to reveal the distinct deformation and fracture mechanisms of the two dual-phase steels. The SQ dual-phase steel exhibited lower strength but superior ductility and impact toughness, which stemmed from the larger deformation of ferrite relaxing the stress concentration generated in martensite during deformation; conversely, in the IA dual-phase steel, ferrite deformation was constrained by the surrounding martensite, and the relatively limited deformation of ferrite could not effectively relax the stress in the deforming martensite, leading to preferential crack initiation in martensite, thus the IA dual-phase steel possessed high strength but low ductility.

Full Text

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Abstract

Investigation of the relationship between microstructure and microscopic deformation behavior of dual-phase steel is crucial for developing high-performance materials. In this work, step quenching (SQ) and intercritical annealing (IA) heat treatments were optimized to produce dual-phase steels with similar martensite volume fractions but with isolated and continuous martensite distributions, respectively. The tensile and impact properties of these steels were characterized, and strain distribution was measured using digital image correlation (DIC). Combined with microcrack observations, different deformation and fracture mechanisms were revealed. Compared to IA steel, SQ steel exhibited lower strength but superior ductility and fracture toughness, attributed to larger deformation in ferrite that resulted in greater stress relaxation in martensite during deformation. In IA steel, ferrite deformation was constrained by adjacent martensite, and the relatively small strain in ferrite could not effectively relax stress in martensite, causing cracks to initiate preferentially in martensite and resulting in high strength but low ductility.

Keywords: dual-phase steel, microstructure, plastic deformation, step quenching, intercritical annealing, digital image correlation (DIC)

Introduction

Dual-phase steels composed of ferrite and martensite have been widely used in the automotive industry since the 1970s due to their excellent mechanical properties and formability [1~4]. The composite structure of ferrite and martensite endows dual-phase steels with continuous yielding, high strain-hardening rates, and good combinations of strength and ductility. However, variations in phase fraction, individual phase properties, and microstructural features can alter macroscopic performance [5~7]. Investigating microscopic deformation behavior, understanding deformation compatibility between phases, and identifying how specific variables affect deformation characteristics and fracture properties can provide valuable guidance for material design and performance improvement.

Martensite morphology and distribution are critical factors influencing microscopic deformation, fracture mechanisms, and ultimately mechanical properties of dual-phase steels [8~14]. For example, Pierman et al. [9] found that dual-phase steels with elongated martensite exhibited better ductility than those with short rod-shaped or equiaxed martensite. Ahmad et al. [12] reported that ductility depended on the relationship between martensite distribution and tensile axis orientation.

Step quenching (SQ) and intercritical annealing (IA) are two common heat treatments for dual-phase steels [15]. SQ involves heating a ferrite-pearlite structure in the austenite region, holding in the two-phase region, and then quenching to produce a dual-phase microstructure with discrete martensite distribution. IA involves direct quenching after holding in the two-phase region, resulting in martensite distributed along ferrite grain boundaries. Previous studies [11~13,15] compared microstructures and mechanical properties of SQ and IA steels with similar martensite volume fractions, analyzing microstructural effects on performance. However, influenced by processing parameters, factors such as grain size significantly affected mechanical properties despite the expected relationship between martensite nucleation sites and ferrite locations. In studies by Das et al. [11] and Ahmad et al. [12], IA steels had much finer martensite grains than SQ steels, making it difficult to isolate the effect of martensite distribution. In work by Su et al. [13] and Kim et al. [15], both ferrite and martensite grain sizes were much larger in SQ than IA steels, but the reported mechanical properties differed between studies.

To isolate the effect of martensite distribution on microscopic deformation behavior and macroscopic mechanical properties, this work produced SQ and IA dual-phase steels with similar martensite volume fractions, ferrite grain sizes, and martensite grain dimensions. Our previous research on strain partitioning in SQ-treated dual-phase steel [16] revealed that strain concentrated significantly in ferrite as deformation bands, particularly at phase interfaces when martensite volume fraction was small. Building upon this, SQ and IA heat treatments were used to produce dual-phase steels with discrete and continuous martensite distributions. Tensile and impact properties were compared, strain partitioning characteristics were analyzed using the non-contact, full-field digital image correlation (DIC) method [16~21], and surface microcracks and fracture surfaces were examined to explain the mechanical performance and fracture features of both steels.

1 Experimental Methods

Commercial 20 steel with composition Fe-0.21C-0.49Mn-0.23Si (wt.%) was used. Two tensile specimen sizes were employed for tensile testing and SEM analysis (surface microcracks and DIC observation). The study compared microstructure, tensile and impact properties, and corresponding fracture surfaces of the two heat-treated steels. To understand the intrinsic reasons for differences in tensile performance, strain partitioning between phases and microcrack distribution near fracture surfaces were analyzed.

Dual-phase steels were heat-treated by controlling austenitizing temperature and time to regulate austenite grain size in SQ samples, thereby indirectly controlling final ferrite and martensite grain sizes. Martensite volume fraction and grain size in both samples were controlled through two-phase region holding temperature, time, and quenching rate. After process optimization, the final SQ and IA heat treatment schedules are shown schematically in [Figure 2: see original paper]. Both used 10 wt.% room-temperature brine quenching, which provides faster cooling and reduces quenching inhomogeneity compared to water [22]. After heat treatment, tensile samples were surface-ground. Small tensile samples for DIC analysis and surface microcrack studies were sectioned from larger specimens and individually polished on one surface, with side surfaces ground using sandpaper. DIC samples were further marked with micro-Vickers indentations to delineate target regions approximately 150 m square within the gauge length.

Microstructures were examined using an ECLIPSE MA100 optical microscope (OM) and JSM 7600F scanning electron microscope (SEM). Tensile tests were conducted on an MTS 809 hydraulic testing machine at crosshead speeds of 2.0 mm/min for standard specimens and 0.5 mm/min for small specimens. Plastic strain during tensile testing was measured using DIC: after etching with 4% nital and photographing the microstructure of target regions, a layer of In particles (0.5-1.0 m diameter) was electrodeposited on sample surfaces as DIC markers. Post-fracture morphology images of target regions were correlated with pre-deformation images using DIC to obtain three strain components and calculate equivalent strain ( ) distribution maps. The equivalent strain formula is:

$$\varepsilon = \sqrt{\frac{2}{3}} \cdot \sqrt{[(\varepsilon_{xx} - \varepsilon_{yy})^2 + (\varepsilon_{yy} - \varepsilon_{zz})^2 + (\varepsilon_{zz} - \varepsilon_{xx})^2 + 6(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2)]}$$

where _{xx} and _{yy} are normal strains in x and y directions, and γ_{xy} is shear strain. Details of the DIC methodology and validation are provided in reference [16]. SEM was used to analyze fracture surfaces of large tensile specimens and surface microcracks near fracture surfaces of small tensile specimens. Additionally, non-standard 5 mm\$$\times 5mm \times$\$55 mm V-notched impact specimens were used for comparative toughness evaluation, with impact fracture surfaces examined.

2 Results

2.1 Microstructure and Mechanical Properties [Figure 3: see original paper] shows OM images of SQ and IA treated samples. The martensite volume fractions and ferrite grain sizes are similar, but martensite distribution and morphology differ significantly. Statistical analysis of multiple regions revealed approximately 35.8% martensite in SQ samples and 38.6% in IA samples. Average ferrite grain size was about 24 m in SQ and 21 m in IA samples. While martensite grains were irregular, their sizes appeared similar in both SQ and IA samples. Microstructurally, SQ-treated samples showed well-connected ferrite grains with discrete, angular martensite islands, whereas IA-treated samples exhibited closely connected martensite distributed along ferrite grain boundaries without angular features, consistent with different martensite nucleation sites during heat treatment [15,23].

Tensile properties of SQ samples with discrete martensite and IA samples with continuous martensite were compared, with tensile curves shown in [Figure 4: see original paper]. Both materials exhibited characteristic dual-phase steel behavior: continuous yielding, low yield strength, high fracture strength, and high strain-hardening rates. However, significant differences existed in yield strength, tensile strength, and elongation. SQ samples had a yield strength of 420 MPa, 24.7% lower than IA samples; tensile strength σ_b of 840 MPa, 16.5% lower than IA samples; and total elongation of 10.8%. The average strain-hardening rate $\bar{h}$ was 4046 MPa, 50% higher than IA samples, as detailed in . Given similar martensite volume fractions and thus similar carbon content in martensite (according to the lever rule), mechanical property differences primarily resulted from martensite morphology and distribution.

Fracture surface comparison revealed distinct features, as shown in [Figure 5: see original paper]. SQ samples exhibited clear ductile fracture characteristics with numerous deep dimples and tear ridges (Fig. 5a), while IA samples showed shallow dimples accompanied by extensive quasi-cleavage facets (Fig. 5b). This indicates that ferrite in SQ samples underwent substantial plastic deformation before fracture, whereas ferrite in IA samples experienced only localized minor deformation, consistent with their respective ductility levels.

Impact toughness comparison showed SQ samples were significantly superior to IA samples. Measured impact energies were 2.84, 2.84, 1.45, and 3.30 J for four SQ samples, averaging 12.13 J/cm^2, compared to 0.55, 0.55, 0.55, and 0.70 J for four IA samples, averaging 2.73 J/cm^2. The average impact toughness of SQ samples was 4.4 times that of IA samples. Although the data showed some scatter, the minimum SQ value exceeded twice the maximum IA value. [Figure 6: see original paper] shows SEM images of impact fracture surfaces. SQ samples exhibited both brittle cleavage facets and numerous dimples with tear ridges (Fig. 6a), while IA samples showed fine quasi-cleavage facets across the entire fracture surface, indicating pronounced brittle characteristics (Fig. 6b). Thus, SQ samples demonstrated superior ductility in tension and higher toughness under impact loading.

2.2 Strain Partitioning Between Ferrite and Martensite DIC analysis yielded two-dimensional equivalent strain distribution maps for multiple target regions in SQ samples with discrete martensite and IA samples with continuous martensite, as shown in [Figure 7: see original paper] and [Figure 8: see original paper] (strain maps overlaid on pre-deformation SEM micrographs). In the strain maps, rectangles indicate deformation bands at phase interfaces, triangles show strain concentration within ferrite, diamonds mark strain concentration in narrow ferrite regions between martensite islands, and circles denote deformation bands passing through martensite. Qualitative analysis revealed that strain concentrated primarily in ferrite, forming distinct deformation bands with different distributions: SQ sample deformation bands concentrated mainly at phase interfaces, while IA samples showed numerous bands passing through martensite. In SQ samples, ferrite/martensite interfaces were the most strain-concentrated regions (rectangles), with some concentration within ferrite (triangles) and only very few cases where deformation bands passed through martensite (circles), always through narrow regions within large martensite islands, consistent with previous research [16]. In IA samples, although deformation bands existed at phase interfaces, the most common feature was bands passing through martensite (circles). Since martensite has low fracture strain, these strain-concentrated locations likely served as crack nucleation sites in IA samples.

Quantitative analysis of extracted ferrite and martensite strain data showed that strain concentration within ferrite was higher in SQ than IA samples. [Figure 9: see original paper] presents equivalent strain frequency distributions for both phases. Despite being harder than ferrite, martensite still underwent some plastic deformation, with IA samples clearly showing greater plastic deformation in martensite than SQ samples. In three SQ target regions, average ferrite strain was 1.9 times average martensite strain, whereas this ratio was only 1.5 in IA samples (with similar overall average strain in target regions). This confirms higher strain concentration in SQ samples and greater plastic deformation in ferrite relative to martensite.

Analysis of surface cracks near tensile fracture surfaces is commonly used to investigate fracture mechanisms [11]. SEM analysis of surface morphology near fracture surfaces was performed on SQ samples with discrete martensite and IA samples with continuous martensite. Microvoids and microcracks were classified based on nucleation location. [Figure 10: see original paper] shows SEM images of surface microcracks, with left and right images of the same field in different modes. Backscattered electron images (BEI) clearly distinguished phases (bright martensite, dark ferrite) (Figs. 10a, c, e), while secondary electron images (SEI) better characterized microvoid and microcrack morphology (Figs. 10b, d, f). Microvoids and microcracks were categorized into three types: ductile microvoids in ferrite (triangles), microvoids and microcracks at phase interfaces (rectangles), and brittle microcracks in fractured martensite islands (ellipses).

Analysis of surface images near fracture surfaces revealed significant differences. In SQ samples, ferrite underwent extensive plastic deformation with numerous prominent slip bands (more evident in BEI). Martensite island fracture was rare, with interface debonding dominant and occasional ductile voids from ferrite fracture. In contrast, IA samples lacked the extensive slip bands and large deformation zones seen in SQ samples. Martensite fractured brittlely before ferrite underwent large deformation, with martensite fracture dominating, plus minor interface debonding and very little ferrite fracture. Thus, the primary crack source in SQ samples was ductile voids at phase interfaces, while in IA samples it was brittle cracks in martensite.

3 Analysis and Discussion

Strain concentration in dual-phase steels arises because ferrite yield strength is much lower than martensite, making ferrite prone to plastic deformation [24~26]. The ability of ferrite to deform continuously in space significantly affects strain concentration and consequently fracture mechanisms and macroscopic properties. The high ductility and toughness of SQ samples result from discrete martensite distribution, allowing continuous ferrite deformation and stress relaxation in martensite. In SQ samples with isolated martensite islands, ferrite grains are interconnected, enabling continuous deformation as long as dislocations can cross ferrite grain boundaries. Large ferrite deformation relaxes stress in martensite, resulting in small martensite deformation, consistent with DIC strain distribution analysis. The large ferrite deformation and small martensite deformation create poor interface compatibility, and the angular interfaces hinder stress-strain transfer, leading to interface debonding and ductile void formation, matching surface microcrack observations. In summary, ferrite deformation capacity is fully utilized in SQ samples, and ductile interface voids resist propagation, giving SQ dual-phase steel high tensile ductility. The similarity in fracture surfaces suggests this also contributes to high impact toughness.

The high strength of IA samples stems from continuous martensite distribution, which hinders continuous ferrite deformation and forces martensite to bear greater deformation. In IA samples with continuous martensite distribution, ferrite grains are separated by martensite. Ferrite deformation is blocked by martensite after small strains, preventing effective stress relaxation in martensite and causing martensite to undergo plastic deformation, consistent with DIC analysis. Since ferrite deformation in IA samples is smaller than in SQ samples while martensite experiences larger deformation, phase interface compatibility is relatively better. However, the low-ductility martensite fractures brittlely after limited deformation, generating cracks that match surface microcrack observations. These cracks then propagate through ferrite via quasi-cleavage, eventually linking to cause brittle fracture. The high-strength martensite in IA samples bears more stress, resulting in higher overall strength than SQ samples.

The strain concentration locations identified by DIC in this work correlate well with microvoid and microcrack locations near fracture surfaces. The qualitative and quantitative microscopic deformation characteristics effectively explain the tensile property differences between IA and SQ dual-phase steels: ductile interface voids in SQ samples correspond to good ductility, while brittle martensite fracture in IA samples corresponds to high strength but low ductility. The macroscopic and microscopic results are self-consistent and credible.

A recent study by Park et al. [10] reported similar findings, showing that dual-phase steel with chain-like continuous martensite distribution had higher strength than that with discrete martensite. However, unlike our work, they found similar elongation for both distributions. In their study, continuous martensite consisted of many small martensite grains aligned in series and distributed along ferrite grain boundaries, which separated during deformation, rapidly increasing microvoid number and maintaining high elongation despite low necking. In our IA samples, larger martensite grains at ferrite boundaries fractured internally during deformation, resulting in low elongation. This does not contradict Park et al. [10]. Our conclusions can explain discrepancies in previous SQ and IA studies. In work by Das et al. [11] and Ahmad et al. [12], SQ samples showed higher strength but lower ductility than IA samples, but their IA steels had much finer martensite grains. In Das et al. [11], large banded martensite in SQ samples forced deformation bands to pass through, causing both martensite fracture and interface damage, leading to high strength but low ductility. In Ahmad et al. [12], SQ steel had coarse martensite grains and 50% volume fraction, isolating ferrite and preventing continuous deformation, resulting in relatively high strength but low ductility, while fine martensite in IA steel increased microvoid number and elongation. Studies by Su et al. [13] and Kim et al. [15] had much larger ferrite and martensite grain sizes in SQ than IA samples, making them incomparable to our work.

Conclusions

1. Dual-phase steels with discrete and continuous martensite distributions in ferrite were produced through step quenching (SQ) and intercritical annealing (IA) heat treatments, respectively, with similar ferrite grain sizes and martensite volume fractions. Tensile and impact testing combined with fracture surface analysis showed that SQ samples had slightly lower tensile strength but superior ductility and impact toughness compared to IA samples.
2. DIC analysis revealed strain concentration locations that correlated well with microcrack/microvoid locations near fracture surfaces, elucidating the origins of macroscopic performance differences.
3. The lower strength but higher ductility of SQ samples resulted from discrete martensite distribution, allowing continuous ferrite deformation and failure initiation by ductile voids at phase interfaces, with minimal martensite deformation and fracture. In contrast, the higher strength but lower ductility of IA samples arose from continuous martensite distribution along ferrite grain boundaries, which hindered ferrite deformation and caused high-strength martensite to deform and fracture brittlely, with cracks propagating through ferrite by cleavage.

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