Fracture behavior of a one-step quenching and partitioning steel characterized using uniaxial tension and double edge-notched tension

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Abstract: The fracture behavior was characterized using uniaxial tension and double edge notched tension (DENT) in a one-step quenching and partitioning steel. This steel consisted of lamellar matrix (tempered martensite and bainitic ferrite lath) together with dispersed blocky and film RA/M (retained austenite and/or fresh martensite). Lamella r structure promoted trans-lath fracture; whereas, blocky RA/M island contributed to ductile fracture in uniaxial tension but induced brittle fracture in DENT test because a higher stress triaxiality in the latter enhanced the rate of martensite transformation and in turn boosted early crack nucleation and propagation.

1. Introduction

Quenching and partitioning (Q & P) steel has received significant interest because of its promising to enhance the combination of strength and ductility since Speer et al. [1] first proposed a Q & P process in 2003. The process includes interrupted quenching from full or partial austenitization condition to martensite transformation region immediately followed by partitioning at the same or a higher temperature. For instance, Q & P steels with simple chemical compositions (0.15–0.30 wt. % carbon, 1.0–2.0 wt. % silicon and 1.5–3.0 wt. % manganese [2]) have an ultimate tensile strength larger than 1000 MPa and a total elongation larger than 20 % due to hard martensitic matrix embedded with retained austenite (RA) stabilized by carbon enrichment during the partitioning process [3].

The relationship between microstructure and tensile properties in Q & P steels has been intensively studied by the adjustment of chemical compositions [3], quenching and partitioning temperatures [3-5], partitioning time [3, 4, 6] and pre-microstructure (before Q & P process) [7]. Whereas, the effect of microstructure on crack resistance (fracture toughness) has been seldom studied. de Diego-Calderón et al. [8] and Wu et al. [5] gave a general conclusion that fracture toughness increased with an increased amount of RA but an increased stability of RA was detrimental to fracture toughness in Q & P steels. In addition, an increased amount of lamellar structure (consisted of film RA and ferritic lath) enhanced fracture toughness via bainite-based Q & P process [9, 10]. However, the specific characterization and corresponding analysis were absent. In the present study, crack propagation in a one-step Q & P steel was studied for the first time. The fracture behavior was comprehensively analyzed using uniaxial tension and double edge notched tension (DENT).
2. Experimental details

A cold-rolled strip of 3 mm thickness was received with a nominal composition of 0.3 wt. % C, 2.5 wt. % Mn, 1.5 wt. % Si, 0.8 wt. % Cr and balanced Fe. The strip was firstly austenitized at 1080 °C for 10 min in a Carbolite muffle furnace and then was moved into an oil bath of 278 °C followed by 40 min holding. A representative microstructure revealed using 2 vol. % nital was shown in Figure 1. It has 13.9 % RA with a carbon content of 0.73 wt. % measured using X-ray diffraction. Based on different greyscales, 7.7±2.2% blocky RA/M (RA and/or fresh martensite) and 19.8±5.6 % film RA/M were manually calculated using Photoshop and Image J. In turn, 13.7% fresh martensite could be deduced from RA/M % – RA %. The matrix consisted of tempered martensite (45.5 % based on Koistinen – Marburger relationship [6]) and balanced bainitic ferrite lath (26.9 %).

Dog-bone tensile samples had a gauge length of 26 mm (parallel to rolling direction) and a width of 6 mm. DENT samples held a length of 100 mm (parallel to rolling direction), a width of 50 mm and a notch of 20 mm at each side in the center. The notch was induced after heat treatment using electric discharge machining (19 mm) followed by fresh blade sharpening (1 mm). Tensile tests were carried out using a screw driven universal testing machine at a cross-head speed of 0.05 mm/s. The microstructure and fracture surface were characterized using scanning electron microscopy.

Figure 1. (a, b) representative microstructures of a one-step quenching and partitioning steel where (b) is the magnification of the rectangle in (a). RA/M is retained austenite and/or martensite.

3. Result

3.1. Uniaxial tension

A continuous engineering stress-strain curve from uniaxial tension was shown in Figure 2(a). The proof yield strength was 895±9 MPa determined according to 0.2% offset method, while the ultimate tensile strength was 1557±3 MPa. The uniform and total elongation were 7.25±0.05 % and 12.20±0.01 %, respectively. The strain hardening exponent monotonously decreased with an increased true strain (Figure 2(b)). This behavior was similar to ferrite-martensite dual phase steel [11], indicating a poor transformation-induced plasticity (TRIP) effect. This can be explained as follows. Firstly, most of RA presented as film shape between ferritic laths (Figure 1), leading to a high stability because of high carbon content and hydrostatic pressure [12]. Secondly, the blocky island of RA/M had a small fraction of 7.7±2.2% and a small size of 2.5±0.4 μm. A smaller size of blocky RA also resulted in a higher stability and, in turn, less TRIP effect [13].

Figure 2(c) shows that the fracture surface consisted of some shallow dimples and lamellar facets indicated by the arrows. The dimples originated from voids nucleation at the interfaces between RA/M and ferritic lath as shown in Figure 2(d), while lamellar facets were probably resulted from lamellar structures.
3.2. Double edge notched tension

Figure 3(a) shows the load-displacement curve of a DENT test where the crack was initiated very early (indicated by the star together with a loud sound during DENT test) and the load rapidly decreased after the maximum load. Corresponding fracture surface adjacent to the notch (Figure 3(b)) consisted of very shallow dimples, lamella facets (indicated by dark arrows) and some cleavages (indicated by white arrows).

In order to study the fracture mechanism, a DENT test was interrupted just after the crack initiation (indicated by the star in Figure 3(a)). It is convenient to characterize the stable crack propagation (Figure 3(c-f)). An overview of the crack (Figure 3(c)) indicated a zig-zag propagation mode, where the crack changed its direction due to somewhat inhibition. This phenomenon is a feature of the enhancement of fracture resistance [14]. On one hand, yellow arrows show blocky and film RA/M along the crack (Figure 3(d)). This indicated that crack predominantly propagated along blocky RA/M and occasionally along film RA/M whose length was in the similar direction of crack propagation. On the other hand, the red arrows show the broken lamella structures (Figure 3(d)), indicating trans-lath fracture. It corresponds to lamella facets observed in Figure 3(b). In addition, this trans-lath fracture can occur between blocky RA/M islands (for example, red circle in Figure 3(d)). Figure 3(e) shows a typical example that lamella structures between cracks beard large deformation, which definitely can enhance the fracture resistance. At the tip of crack, it was also observed that the lamellar structure indeed held a large deformation as indicated by the red circle (Figure 3(f)). In the right-hand side, the nucleation of two voids was detected along blocky RA/M islands. Therefore, the crack would probably change it direction to the right side due to the inhibition of lamella structure.

A schematic illustration of fracture mechanism in this one step Q & P steel is shown in Figure 4. First, crack nucleates at the boundaries of blocky RA/M islands. The lamellar structure between blocky RA/M will bear large deformation due to stress concentration, leading to trans-lath fracture.
Occasionally, crack also propagates along film RA/M whose length is approximately parallel to the direction of crack propagation.

Figure 3. (a) Load-displacement curve of a DENT test; (b) fracture surface; (c) stable crack propagation interrupted just after the star in (a); (d, e, f) corresponding microstructure along the crack.
4. Discussion

In comparison with fracture surfaces observed after uniaxial tension (Figure 2(c)) and DENT test (Figure 3(b)), both of them contained lamellar facets, while the main difference is that many dimples were observed in the former and some cleavages were identified instead of dimples in the latter. This is ascribed to a higher stress triaxiality during the DENT test [15], which led to quick transformation of blocky RA to brittle martensite. Neighboring martensite could form a brittle necklace structure, which would facilitate the cleavage fracture [16]. Meanwhile, the uniaxial tension had a higher strain hardening ability because of a slower RA-to-martensite transformation, which promoted void nucleation by the inhibition of crack propagation.

Most of RA presented as film shape (Figure 1) had a very high stability because the high carbon content was efficiently enriched from neighboring ferritic laths due to a high ratio of interface area to the volume and hydrostatic pressure induced by ferritic laths helping accommodate external stress [12]. As demonstrated using in-situ electron backscattering diffraction during uniaxial tension [17], most of film RA did not transform to martensite before necking. Thus, film RA could have the same behavior of martensite transformation during post-necking in the uniaxial tension and DENT test. In turn, the film RA did not contribute much to tensile properties but it increased the fracture resistance. As observed in Figure 3(d), lamellar structure between blocky RA was broken in a trans-lath mode, which related to lamellar facets in Figure 3(b). Similarly, the lamellar facets observed in Figure 2(c) were produced during the post-necking deformation (which also had a large stress triaxiality).

Generally, blocky RA/M island is beneficial to enhance tensile properties while lamellar structure (film RA clamped by ferritic laths) contributes to fracture resistance. This difference behavior of blocky island and lamellar structure in uniaxial tension and DENT test gives an indication of microstructure design for the counterbalance between tensile properties and fracture resistance.

5. Conclusion

Uniaxial tension and DENT test were used to study the role of blocky island and lamellar structure in the fracture behavior of a one-step Q & P steel. In uniaxial tension, blocky RA/M island contributed to local strain hardening and in turn enhanced tensile properties; while quick blocky RA-to-martensite transformation induced by a high stress triaxiality in local deformation during DENT test decreased fracture resistance. A high stability of film RA contributed little to tensile properties but it was beneficial to the enhancement of fracture resistance due to its inhibition of crack propagation.
Conflicts of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

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