HYDROGEN EMBRITTLEMENT BEHAVIOR OF A 1.5 GPa CLASS DUAL-PHASE STEEL

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Abstract
In the current work, using tensile tests, we evaluate the hydrogen embrittlement behavior of a 1.5 GPa dual-phase (DP) steel consisting of ~75% martensite. Contrary to previous studies of DP steel with ultimate tensile strength (UTS) ≤1.2 GPa, a predominant brittle fracture is observed in the DP steel in the absence of hydrogen. Conventionally, in the absence of hydrogen, ferrite is reported to arrest cracks, resulting in a ductile fracture. However, ferrite undergoes {100} brittle cleavage cracking. Furthermore, the morphology of the martensite crack is found to have an influence on ferrite {100} cleavage cracking. The micro-mechanisms are presented in detail. Subsequently, we investigated the effect of hydrogen on the degradation of tensile properties. Hydrogen caused a significant deterioration of UTS, from 1.5 GPa to 0.9 GPa. The damage mechanisms of hydrogen-induced fracture are discussed in detail.

1. Introduction
As of 2017, the transport sector is responsible for 25% of global carbon dioxide (CO_2) emissions [1]. A 10% vehicle weight reduction can improve fuel consumption by 6-8% [2]. Such a vehicle weight reduction can be realized through lightweighting. Using advanced high-strength steels (AHSSs) with a higher strength-to-weight ratio is an effective method to achieve weight reduction. To this end, AHSSs with ultimate tensile strength (UTS) ≥ 1.5 GPa are of great interest. However, with an increase in strength, the susceptibility to hydrogen embrittlement (HE) also increases, necessitating the study of HE.

Dual-phase (DP) steels are one of the key classes of AHSSs, given their lean alloying and simple thermomechanical processing. Until now, the study of failure mechanisms in DP steels was confined to DP steels with ultimate tensile strength (UTS) ~≤1.2 GPa [3]. In the present work, we elucidate the damage mechanisms, both in the absence and presence of hydrogen, in a 1.5 GPa class DP steel. We achieve this by coupling electron backscatter diffraction (EBSD) studies with electron channeling contrast imaging (ECCI).

2. Results
The tensile properties of the DP steel are summarized in Table 1. In the absence of hydrogen, the DP steels are typically considered resistant to brittle fracture because of the crack-arresting behavior of the ferrite. However, the 1.5 GPa class DP steel exhibited predominantly brittle fracture [4]. The crack initiation occurred via martensite cracking along prior austenite grain boundaries (PAGBs). Two distinct crack morphologies were identified: sharp and blunt crack. It is important to note that no martensite-ferrite boundary decohesion was observed. A mixed mode fracture was observed in martensite; intergranular fracture (along PAGBs) and transgranular fracture (E.g., cleavage along {110} planes). Ferrite exhibited predominant {100} cleavage cracking accompanied by occasional ductile fracture. Furthermore, it was observed that the martensite crack morphology influenced the ferrite {100} cleavage cracking. We clarify the origins of brittle cracking in ferrite and subsequently, explain the damage micro-mechanisms at play.

Hydrogen was introduced via electrochemical charging for 12 hours in a 3 wt. % NaCl aqueous solution consisting of 3 gL^{-1} of NH_4SCN at a current density of 1 Am^{-2}. Thermal desorption spectroscopy (TDS) was used to measure the hydrogen content. In the present work, the hydrogen content is defined as the cumulative desorbed hydrogen content from room temperature to 523 K, which is 3.79 mass ppm. The premature failure caused by hydrogen is evident from the tensile properties in table 1. We discuss in detail the hydrogen embrittlement mechanisms.

Table 1 Summary of the tensile properties

Condition	Strain rate (s^{-1})	UTS (GPa)	Elongation (%)
Without Hydrogen	10^{-3}	1.5	5.2
Hydrogen Charged	10^{-3}	1.3	1.2
	10^{-4}	0.9	0.6

3. Conclusions

We compare and contrast the damage mechanisms in a 1.5 GPa dual-phase steel both in the presence and absence of hydrogen through electron backscatter diffraction measurements and electron channeling contrast imaging.

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