Harmless Preexisting Crack in Structures Made of Hydrogen-Embrittlement Sensitive Materials under Monotonic Tension

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Abstract. The interaction of hydrogen with the dislocations in the plastic zone of preexisting cracks (pre-cracks) in engineering components generally degrades the ultimate tensile strength (UTS). Hence, the crack effect coupled with hydrogen-embrittlement (HE) is widely believed to be harmful in engineering applications. However, in this study, the UTS of shallow pre-cracked structures made of interstitial-free (IF) steel, which is a hydrogen-embrittlement sensitive material, may not be wakened in hydrogen environment. Results of cylinder specimens with saturated hydrogen were experimentally and microscope-analytically compared with that of specimens without hydrogen. Then, this anti-common-sense influence of hydrogen was attributed as follows: (1) the crack propagation assisted by hydrogen enhanced localized plasticity (HELP) is stable before the onset of plastic instability because of high fracture instability toughness; and (2) the plastic strain localization at tips of the pre-crack and secondary cracks resists the onset of plastic instability. Additionally, the applicability of such a shallow crack effect coupled with HE presented by this study in engineering applications was discussed.

1. Introduction
Preexisting cracks (Pre-crack) in engineering components are almost inevitable with current technology. They are significant local stress intensifiers that stimulate the dislocation motion from the crack-tip. As the primary conductor of plastic deformation, dislocations can interact with hydrogen and result in hydrogen-embrittlement (HE) phenomenon [1], which manifest a degradation in mechanical properties of HE sensitive materials. Meanwhile, hydrogen is an important kind of clean energy [2] with abundant applications. Hence, there is an increasing need for studies of HE effects on pre-cracked structures.

Conventional considerations about the hydrogen-assisted failure of pre-cracked structures mainly focus on the mechanical properties dominated by crack propagating behaviors, namely, the onset of unstable crack propagation stimulated by hydrogen enhanced localized plasticity [3] (HELP) and hydrogen-enhanced decohesion effect [4] (HEDE). Ultimate tensile strength (UTS) is a vital mechanical property of pre-cracked structures that may be decreased dramatically by the unstable crack propagation in hydrogen environment [1]. However, the UTS is not only governed by the unstable crack propagation, but also by the plastic instability in one yield section [5]. The latter may occur in a structure with a shallow pre-crack because of a remarkably high fracture toughness [6].
technology advances, engineering components rarely contain very deep pre-cracks. Nevertheless, few investigations report the UTS of shallow pre-cracked structures in hydrogen environment.

This study aimed to provide a preliminary exploration in shallow pre-cracks effects on the UTS of structures governed by plastic instability in hydrogen environment. The specimens were made of interstitial-free (IF) steel, which stands for a major group of bcc steels used in the automotive industry. It owns the excellent ductility, simple metallurgical microstructure, and significant HE sensitivity [7]. Fully electrochemical hydrogen pre-charged specimens (with the in-situ charging during monotonic tension to maintain the hydrogen saturation) ware experimentally and microscope-analytically compared with that of uncharged specimens (without in-situ charging). Results showed that shallow cracks with HE did not weaken the UTS governed by plastic instability. The underlying reason is that crack propagation assisted by HELP was stable before the onset of plastic instability; meanwhile, the plastic strain localization at crack-tip even resists the onset of plastic instability. This anti-commonsense effect of shallow cracks in hydrogen environment was considered to have broad applicability in engineering because it is not a material intrinsic property.

![Figure 1. Dimensions of specimens with shallow crack-like notch.](image1)

**Figure 1.** Dimensions of specimens with shallow crack-like notch.

![Figure 2. Schematic of electrochemical hydrogen charging.](image2)

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![Figure 3. Tensile stress-displacement curves of pre-cracked specimens.](image3)

**Figure 3.** Tensile stress-displacement curves of pre-cracked specimens.
2. Experimental Procedure

2.1. Material and Specimen
The chemical composition of IF steel used in this study was C = 0.0019, Si = 0.009, Mn ≤ 0.003, P ≤ 0.002, S ≤ 0.0003, Ti = 0.029, Al = 0.028, N = 0.0008 and O = 0.0015 (wt.%). The interstitial C and N were completely trapped in Ti-containing precipitates, thus there were no interstitial solute atoms. IF steel was heat-treated by two hours annealing and then furnace cooled to the room temperature to reduce anisotropy. The averaged grain size and hardness were 5.2 μm and 62 HV, respectively.

The dimensions of cylinder specimens were shown in figure 1. The pre-cracks were introduced by grooving crack-like notches in the middle of gages [8]. It was expected that the UTS (the maximum load divided by the initial intact cross-sectional area) was governed by plastic instability, so that pre-crack depths should be very shallow to ensure a high fracture instability toughness [9]. In this study, the pre-crack depths were fixed at about 1% of the intact cross-sectional radius. After machining, the gages of specimens were buff polished.

2.2. Hydrogen Charging
The electrochemical hydrogen charging [10] was adopted in this study, as shown in figure 2. A working condition of pre-cracked engineering components continuously exposed to hydrogen was assumed. Hence, the pre-cracked specimens were fully pre-charged in 3% NaCl aqueous solution with 3g/L NH₄SCN for one hour at a current density of 10 mA/cm² to ensure that the hydrogen was saturated in specimens [1].

2.3. Monotonic Tensile Tests
Two pre-charged specimens were stretched at an initial strain rate of 10⁻⁴ /s. For all pre-charged specimens, the in-situ charging with the same electrochemical condition of pre-charging was conducted to maintain the hydrogen saturation. The solution was continuously dripped into the container to keep the gage below the liquid level, as shown in figure 2. By contrast, an uncharged specimen was stretched at the same initial strain rate of the pre-charged specimen. Additionally, one of the pre-charged specimens was manually interrupted at the UTS, and then it was longitudinally cut and polished. It was used for determining the physical meaning of UTS and fracture behavior observation. The microscopic analysis was conducted by scanning electron microscope (SEM) with electron backscatter diffraction (EBSD) at 15 kV.

Figure 4. Fracture surface of pre-cracked specimens: (a) in normal environment with cup-and-cone appearance, and (b) in hydrogen environment.
3. Results and Discussion

Figure 3 shows the tensile stress-displacement curves of pre-cracked specimens. An apparent degradation of ductility in the presence of hydrogen indicates that pre-cracked specimens were sensitive to HE. However, the interaction of hydrogen with pre-crack had no influence on the UTS. This phenomenon antis the commonsense of HE effects on pre-cracked structures. Additionally, the UTS of all pre-cracked specimens was identical to that of the crack-free specimen in normal environment (the dashed line in figure 3).

Figure 4a shows the fracture surface of the pre-cracked specimen in normal environment. It presents a ductile failure with a cup-and-cone appearance, which is typically origins from the internal crack initiation by void initiation, growth, and coalescence after necking [11, 12]. Moreover, the final rupture occurs in the intact cross-section so that the pre-crack should have a remarkably high fracture instability toughness. Therefore, the failure of the pre-cracked specimen in normal environment was governed by plastic instability.

The pre-cracked specimens with hydrogen own a different appearance, as shown in figure 4b and figure 5. The pre-crack propagated, and the final rupture moved to the pre-cracked cross-section, as shown in figure 5a. There are two kinds of damage patterns in the fracture surface, namely, the quasi-cleavage mixed with intergranular fracture, as shown in figures 5b and 5c, and the dimple area located in the specimen center, as shown in figures 5a and 5d. The transition of two kinds of damage patterns is considered as the onset of unstable crack propagation, because the accelerating local strain rate at an unstable crack tip can suppress the susceptibility to HE [1]. Hence, compared to figure 4 of the uncharged specimen, HE effect is significant in figure 5 of the pre-charged specimen.

Figure 5. Damage patterns in fracture surface of pre-cracked specimen in hydrogen.

Figure 6 shows the microscopic observations of the pre-cracked specimen interrupted at the UTS in hydrogen environment. The pre-crack advancing at UTS in figure 6a is much shorter than that at the boundary between the quasi-cleavage mixed with intergranular fracture and dimple area in figure 5a. The initiation of secondary cracks as the form of intergranular fracture was almost homogenous in the specimen, as shown in figures 6a and 6b. Moreover, the striation-like pattern [13] on intergranular fracture surface in figure 6c, and the high kernel average misorientation (KAM) in figure 6d near the void initiating along the grain boundary infers that the intergranular fracture was caused by high plastic deformation related to HELP instead of the decohesion mechanism (HEDE). Hence, secondary cracks were probably initiated by extensive plasticity before the pre-crack propagates to their places. These facts indicate that the pre-crack propagation, which has a form of secondary crack initiation and progressive coalescence with the pre-crack, was still stable at the UTS so that the physical meaning of the UTS is plastic instability even in hydrogen environment. According to the abovementioned, the
crack effect coupled with hydrogen effect may not degrade the UTS governed by plastic instability. Both the crack effect and HE effect (especially for HELP) stimulate the plastic strain localization at the crack tip or microscopic trapping sites. However, in this study, plastic instability in one yield cross-section is a macroscopic failure that occurs only if the work hardening increment is insufficient to offset the rising load. The plastic strain localization caused by crack and HE effects naturally have a function on competing with the macroscopic failure of plastic instability. Hence, for very shallow pre-cracks, the crack and HE effects may resist the onset of plastic instability so that the UTS would not decrease.

![Microscopic observations of the pre-cracked specimen interrupted at UTS in hydrogen environment. Figure 6.](image)

Such harmless preexisting cracks are considered to have broad applicability in engineering applications. In the first, the fracture instability toughness of shallow crack is not a material intrinsic property [9, 11]. It strongly depends on the geometric configuration, such as the pre-crack depth and structure size, particularly for the structures made of ductile materials. In the second, the onset of plastic instability is determined by the work hardening condition, which is strongly depended on stress and strain fields in one yield cross-section. Naturally, stress and strain fields are sensitive to the geometric variation no matter due to design or damage. Therefore, if a pre-cracked structure is made of ductile strain-hardening materials, which covers most commercial metals [14], harmless pre-cracks in hydrogen environment probably exist. This speculation needs further systematic study.

4. Conclusions
Shallow cracks with HE may not weaken the UTS governed by plastic instability because crack propagation assisted by HELP was stable before the onset of plastic instability; meanwhile, the plastic strain localization caused by cracks and HE effects even resists the onset of plastic instability. It is considered that the shallow crack effect of anti-commonsense in hydrogen environment depends not
only on the material strain-hardening properties, but also on the geometric properties. Hence, harmless pre-cracks in hydrogen environment probably exist in abundant engineering applications.

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