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Hydrogen Embrittlement in Shot-Peened Steel

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Abstract

This work investigates the role of shot peening on hydrogen embrittlement resistance in quenched and tempered 1070 steel. Thermal desorption spectroscopy results revealed that shot-peened specimens contained nearly twice the hydrogen (H) content of unpeened samples when charged under the same electrochemical conditions, suggesting the introduction of additional trapping sites occur during peening. The mechanism underlying this behavior can be associated with increased dislocation density and is more consistent with the HELP mechanism. Residual stress measurements show a significant relaxation of compressive stresses in shot-peened specimen after H charging, indicating H enhanced dislocation rearrangement. Both unpeened and peened specimens exhibited reduced ductility and strength after H charging; however, the peened samples demonstrated a smaller reduction (72.6% vs 55.8%). Despite higher overall H uptake, the shot-peening reduced susceptibility to embrittlement as compared to the unpeened condition.

Keywords Hydrogen embrittlement, HELP mechanism, TDS

Introduction

Hydrogen embrittlement (HE) is a degradation process in which the ingress of atomic hydrogen (H) into metals reduces ductility and strength [1]. Among the various mechanisms proposed to explain HE, the Hydrogen Enhanced Localized Plasticity (HELP) mechanism describes how H facilitates dislocation motion, thereby enabling localized plasticity [2]. Shot peening has been shown to improve resistance to HE by altering surface microstructures and modifying H uptake behavior [3–6]. Increasing the intensity of shot peening generally leads to higher compressive residual stresses at the surface, resulting in a less pronounced loss of ductility under H exposure [3].

In our previous work [7], we observed that the compressive residual stress in shot-peened specimens relaxed after H charging and the associated dislocation density decreased. These findings highlighted the importance of microstructural features, particularly dislocation density and H trapping sites, in governing embrittlement behavior. By influencing how H is absorbed, trapped, and redistributed within the lattice, these features directly affect both the mechanical response and fracture mode [8,9].

Thermal Desorption Spectroscopy (TDS) is a powerful technique for characterizing H trapping behavior, as the spectrum enables the separation of reversible traps from irreversible traps with stronger binding energies [10–12]. By quantifying the total H content and the distribution of H released at different temperatures, TDS provides a direct link between H uptake, microstructural modifications, and mechanical response. In the context of shot-peened steels, TDS is valuable for identifying how dislocations and residual stress influence H correlates with ductility loss.

The present study aims to untangle the effects of shot peening on HE in quenched and tempered 1070 steel by comparing the behavior of peened and unpeened specimens. Specimens were subjected to 72 hours of cathodic H charging, followed by residual stress characterization using X-ray diffraction (XRD), three-point bending tests to assess mechanical response, and TDS measurements to quantify H uptake.

Experimental Procedures

Cathodic hydrogen charging was conducted on quenched and tempered 1070 steel Almen strips (45–48 HRC) using an electrolyte of 0.5 M H_2SO_4 with 1 g/L thiourea (a H recombination poison) at a current density of 0.7 mA/cm² for 72 h. Both sides of the samples were charged simultaneously. Then three-point bending tests were performed with a span length of 16.0 mm and a crosshead speed of 10 mm/min, applying the load such that the peened surface was in compression; force–displacement data were subsequently converted to stress–strain curve. H content quantification was conducted by thermal desorption spectroscopy (TDS) by ELTRA H-500 Hydrogen Determinator, with specimens heated at 100 °C/s to ~900 °C to measure total H content. For each test condition, a single sample was tested.

Results

Figure 1. shows pictures post three-point bending of specimens under different conditions: (top) unpeened as-received, (middle) shot-peened, and (bottom) shot-peened with H charging for 72 h (HC72h). Note that during hydrogen charging, the specimens are immersed in electrolyte, exposing both sides of the strips to hydrogen, and so the tensile side of the bend test should have high solute H. Figure 2 shows the residual stresses as a function of depth from the surface of peened and unpeened under 72 h of HC. The measurements were carried out 72 h after charging to allow reversible H to outgas under ambient conditions. Hydrogen charging alone leads to no significant change in residual stress in these quench and tempered steels as shown in unpeened specimen. For the case of shot-peened specimens, the as-peened sample exhibits high compressive residual stress near the surface, with a maximum compressive biaxial stress at a depth between 100-200 µm under the surface. After 72 h hydrogen charging, a noticeable relaxation of compressive stress occurs, changing both the stress on the surface and decreasing the depth and maximum value of the compressive stress. This trend is consistent with observations reported in earlier studies [7]. The observation implies that hydrogen charging promotes the rearrangement and redistribution of dislocations in the peened samples.

Figure 3 presents the bending stress–strain response of unpeened and shot-peened specimens in the as-received condition and after 72 h of hydrogen charging, followed by 72 h exposure to ambient conditions. In the as-received state, the stress at which yielding occurs is lower for the shot-peened specimen compared to the unpeened specimen. This response is attributed to the bending configuration, where the peened surface is placed in compression, and the residual compressive stress present in the specimen contributes to earlier yielding. After hydrogen charging, the unpeened specimens display 72.6% reduction in ductility. In contrast, the shot-peened specimens show 55.8% decrease in ductility, indicating that shot peening provides resistance to hydrogen-induced degradation.

Figure 4(a) shows the TDS spectra of the unpeened and peened sample after 72 h cathodic hydrogen charging. Note that TDS tests were carried out within 1 h after HC72h, which differs from the timing of the residual stress measurements and bending tests (which could have additional H outgassing). As these are preliminary results, the tests were performed to capture the H content near its peak. The integrated peak area was used to determine the H content relative to the initial specimen weight. The shot-peened sample contained 59.6 ppm H, nearly twice of 27.3 ppm measured for the unpeened specimen. In addition to this higher H uptake, distinct differences are evident in the desorption features. Figure 4(b), (c) and Table 1 present the deconvoluted peaks from the TDS spectra along with the corresponding quantitative results. The first desorption peak, located at approximately 260 °C, corresponds to about three times the H content in the shot-peened specimen compared to the unpeened one. Unlike the first peak, the second peak appears at 344 °C for the unpeened sample and at 415 °C for the shot-peened sample, with the associated H content in the peened specimen being roughly twice that of the unpeened counterpart. Since the specimens expose both the peened and unpeened sides of the strip to hydrogen, it can be conservatively concluded that the difference is mainly due to the peened side.

Figure 1. Post-bending photos. From top to bottom: unpeened as-received, as-peened, peened HC72h.

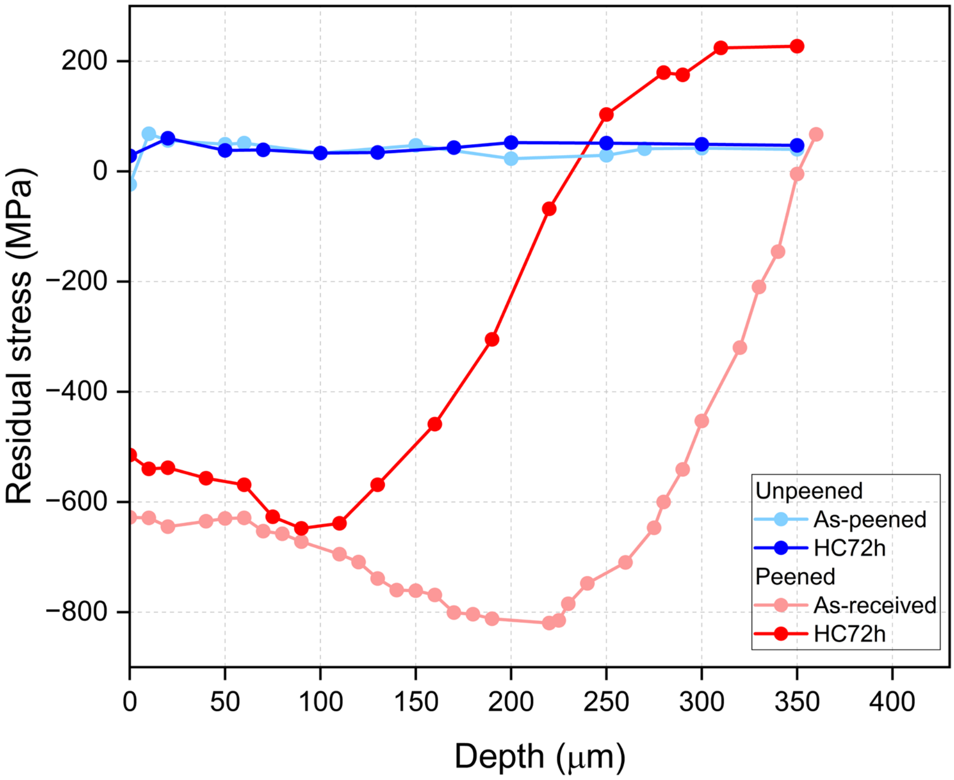

Figure 2. Residual stress profiles with the longitudinal depth from the surface in the unpeened of as-received and electrochemically H charged specimens and shot-peened of as-peened and electrochemically H charged specimens.

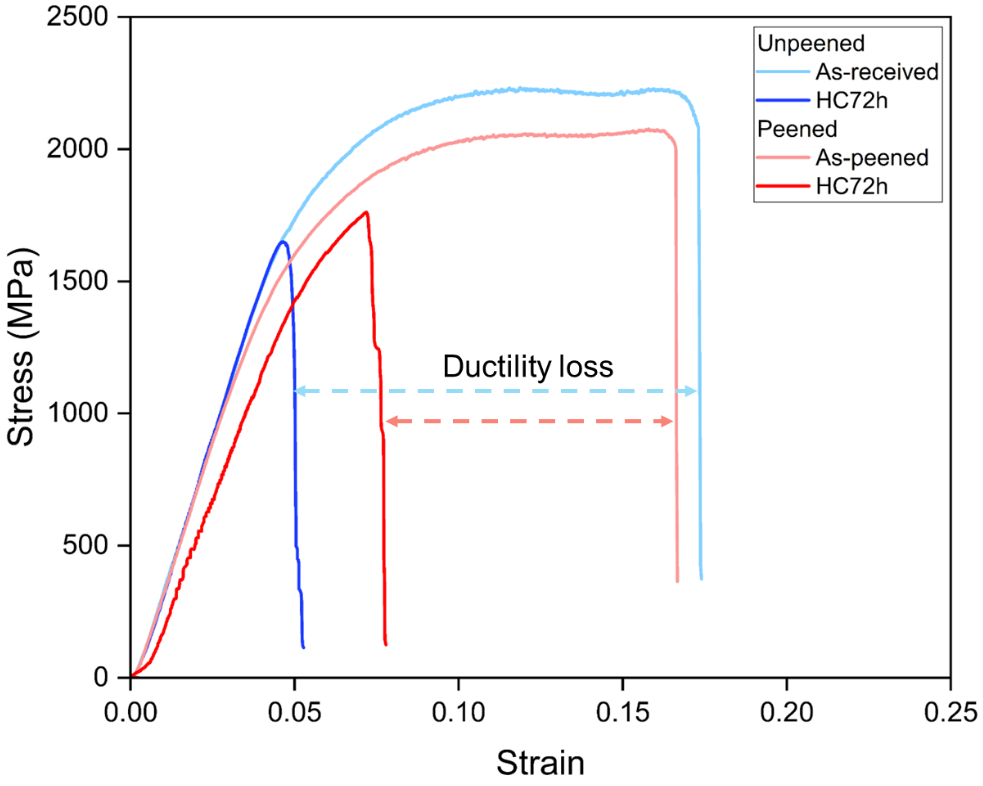

Figure 3. Three-point bending test results of unpeened and peened specimens in the as-received condition and after hydrogen cathodic charging for 72h.

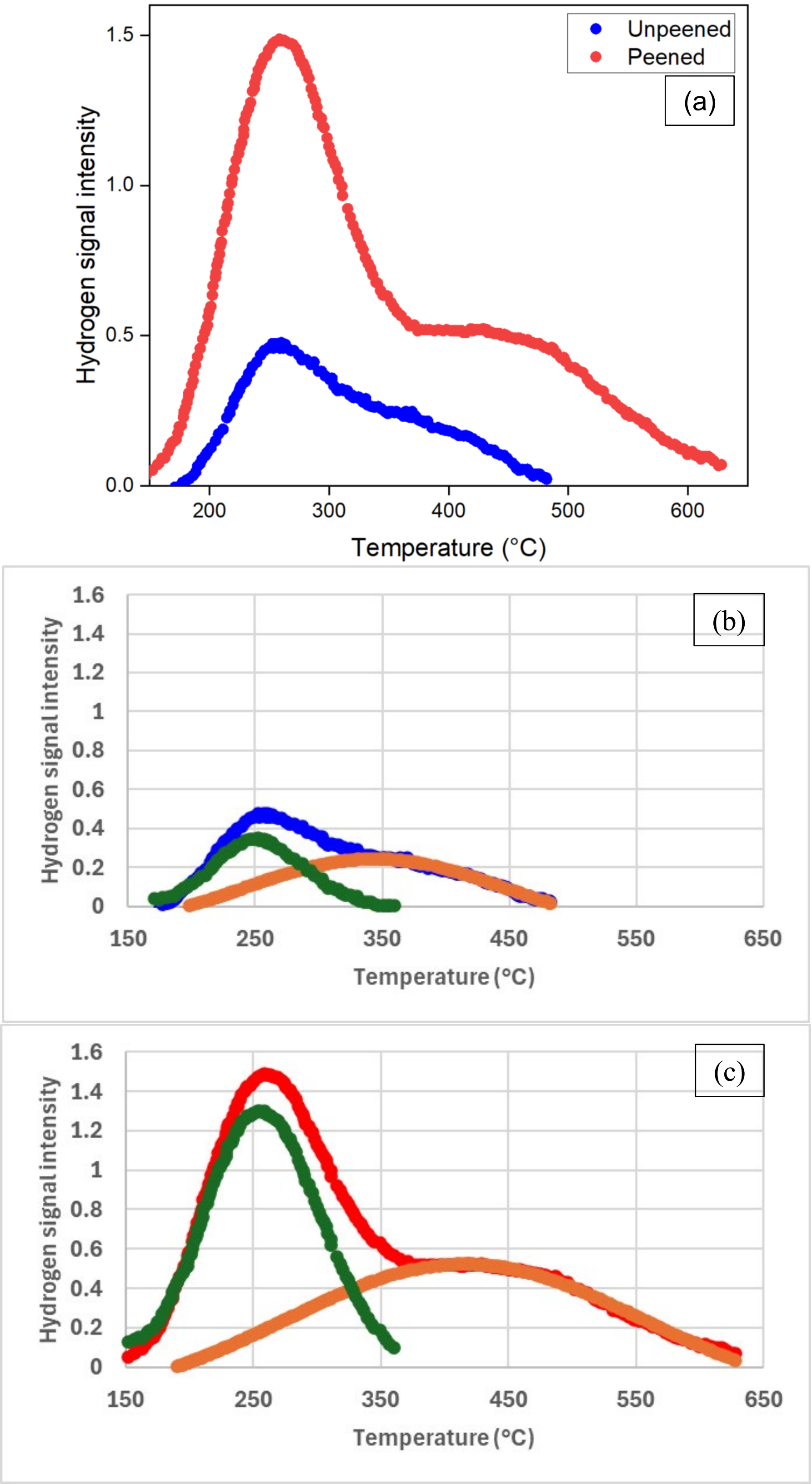

Figure 4. (a)TDS spectra of unpeened (blue) and peened (red) specimen after 72 h cathodic H charging. The total H content: 27.3 ppm for unpeened and 59.6 ppm for peened sample. Deconvolution peaks for TDS spectrum of (b) unpeened sample and (c) peened sample, the first peak (likely reversible H) is shown green; the second peak (deeply trapped H) is shown in orange.

Table 1. Summary of H content in unpeend and peened 1070 steel after electrochemical hydrogen tesing, values extracted from data shown in Figure 4.

	Unpeened		Peened	
Peak	Peak1	Peak2	Peak1	Peak2
Integrated Area	3252.65	6084.75	23612.76	24049.78
H content (ppm)	9.51	17.79	29.53	30.07
Relative ratio	34.8%	65.2%	49.5%	50.5%

Discussion and Conclusions

The results of this study highlight the interaction between residual stress, dislocation structures, and H trapping in shot-peened steels. As shown in Figure 2, specimens subjected to shot peening exhibited a significant relaxation of compressive residual stress after hydrogen charging, whereas unpeened specimens showed little change in stress or in stress state. This behavior can be understood in terms of HELP mechanism, where solute H reduces the resistance to dislocation motion and promotes localized plasticity. The existing high dislocation density created from peening in the surface, coupled with the residual stress from peening, allows for the subsequent dislocation motion. The increased dislocation mobility induced by H facilitates dislocation rearrangement, which contributes to the observed relaxation of residual stress.

The thermal desorption spectra in Figure 4 provides further insight into this process. The two desorption peaks are interpreted as representing different types of H traps: the first, at lower temperature, corresponds to the traps with lower binding energy such as interfaces or lattice sites, while the second peak at higher temperature corresponds to the traps with stronger binding energies, such as the dislocations introduced by shot peening. Although factors such as surface roughness and grain refinement may also influence H uptake, the second peak is most likely to be irreversible traps. Further studies are needed to untangle the results shown in Figure 4 and classify the contribution of each trapping site.

These findings connect directly to the mechanical response observed in Figure 3. Despite absorbing nearly twice as much H as the unpeened specimens, the shot-peened specimens showed a smaller reduction in ductility. Irreversible H facilitates dislocation rearrangement, which accommodates localized plasticity and delays the onset of fracture. The HELP mechanism is likely what enabled shot-peened specimen to sustain better mechanical performance under H exposure compared to unpeened specimen.

In conclusion, shot peening alters HE behavior in quenched and tempered 1070 steel. Although peened specimens absorb more H overall, the trapping of H at dislocation sites and the improved dislocation mobility under the HELP mechanism mitigate the adverse effects of H ingress. These results suggest that shot peening can possibly serve as an effective surface treatment to enhance resistance to hydrogen embrittlement by promoting beneficial H trapping and stabilizing mechanical performance in high-strength steels.

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