Interactions Between Peened Surfaces and Solute Hydrogen in Steels

Jia-Huei Tien, Megan Reger, David R. Johnson, David F. Bahr
School of Materials Engineering, Purdue University. West Lafayette, Indiana 47907 USA

ABSTRACT

Once a peened surface is placed in service, the interaction with the environment can alter the state of the material. This paper demonstrates how hydrogen, a common element which can dissolve into many metallic systems, can decrease the compressive residual stress in shot-peened steels.

INTRODUCTION

Solute hydrogen in steels can dramatically reduce the toughness of the material. Hydrogen embrittlement is a perennial problem for steels in corrosive environments where the hydrogen uptake is driven by electrochemical corrosion reactions. In these cases, the contact with hydrogen is often not desired but unavoidable. With the increased interest in de-carbonizing power systems, there is added opportunities for situations where hydrogen gas will be in contact with steels as an energy carrier for power generation, via fuel cells or combustion where contact with hydrogen is part of the design. The decomposition of H_2 to H, which may occur during combustion processes, provides yet another pathway for dissolving atomic H into steel. In either planned or unavoidable scenarios, dissolving H into the steel requires both entry and subsequent diffusion into the alloy. When in the steel, H can be mobile or trapped to features such as precipitates, grain boundaries, or dislocations.

Shot peening and similar surface processing methods, in general, produce biaxial compressive stresses on the surface of material. They add plastic deformation content to those surfaces that would be likely to be exposed to hydrogen, and they alter surface films or micro-scale surface roughness on peened materials. The interplay between stresses in the near-surface region of steels, the increase in dislocation density due to plastic deformation, and how hydrogen enters and subsequently diffuses into the sample is complex. Ball burnishing has been suggested to decrease H uptake [1], and in ferritic-pearlitic steels shot peening can change the number of H-trapping sites [2,3]. Recent studies from Kawamori et al [4] showed that when peened medium carbon steels are electrolytically charged, peening could either improve or have deleterious effects on H embrittlement due to changes in surface films, H uptake, and the extent of compressive stresses in the material.

This study aimed to examine peened medium carbon steel samples (using commercially available Almen strips) to determine if electrolytic hydrogen charging would change the compressive stress profile of peened parts.

PEENING AND CHARGING PROCEDURES

Almen "A" strips (provided by Electronics Incorporated) were peened using S230 media in a commercial system (courtesy of Progressive Surface). A series of samples were peened to an arc height of ≈0.020". Residual stresses in the samples were measured using a PulsTec µ-X360s residual stress analyzer; both surface stresses and depth profiles were measured pre- and post-electrochemical charging. Electrochemical H charging was in 0.5M sulfuric acid with 1g/L Thiourea at a current density of 35 mA/cm^2. The charging time was between 24 and 120 hours.

RESULTS

To demonstrate that the H charging conditions indeed led to hydrogen embrittlement, a simple impact test post charging was carried out on a peened and a charged specimen. As shown in Figure 1, the peened sample bent while the charged

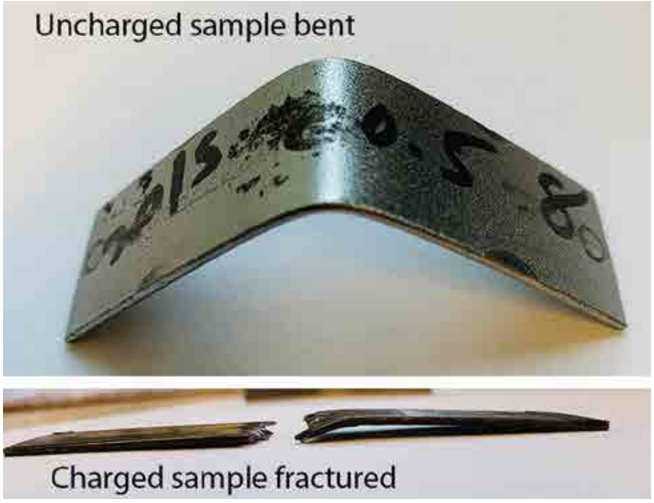

Figure One

specimen broke easily under the same impact. This isn't surprising but is an effective demonstration of the decrease in toughness when H is dissolved in the steel. As samples were hydrogen charged over time, at various stages the charging was paused, a stress measurement taken, and then the sample was re-submerged in the electrolyte for continued charging. Figure 2 demonstrates the compressive surface stress during the charging process (negative values are larger compressive stresses. The key feature here is that the surface stress decreases with increasing charging time, but when the sample is removed from the solution and rests in the lab environment, the surface stress recovers slightly. Solute hydrogen in the steel is influencing (likely adversely) the beneficial compressive stresses generated from peening, but these changes are not completely permanent. Hydrogen is known to diffuse rapidly in steels, and the partial recovery over time indicates there is both a transient and permanent effect on the stresses.

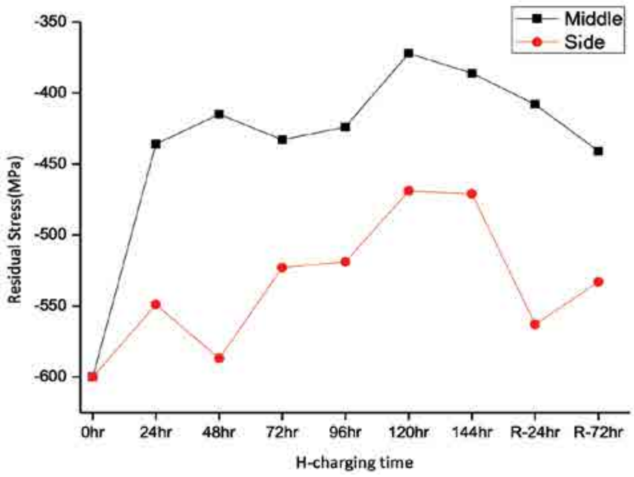

Figure Two

The surface stress is not the only value used in assessing the beneficial aspects of peening as the complete depth profile also impacts processes like resistance to fatigue cracking. Figure 3 shows the depth profile on the peened and the unpeened (back) surfaces (both were hydrogen charged). Hydrogen charging decreased the maximum compressive stress but moved it deeper into the sample.

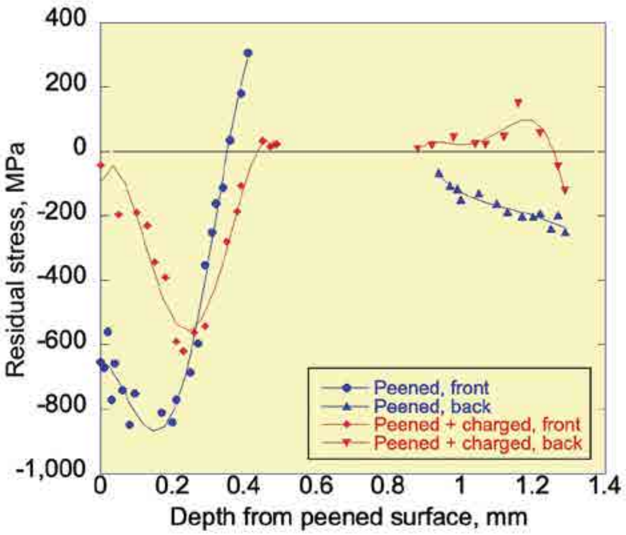

Figure Three

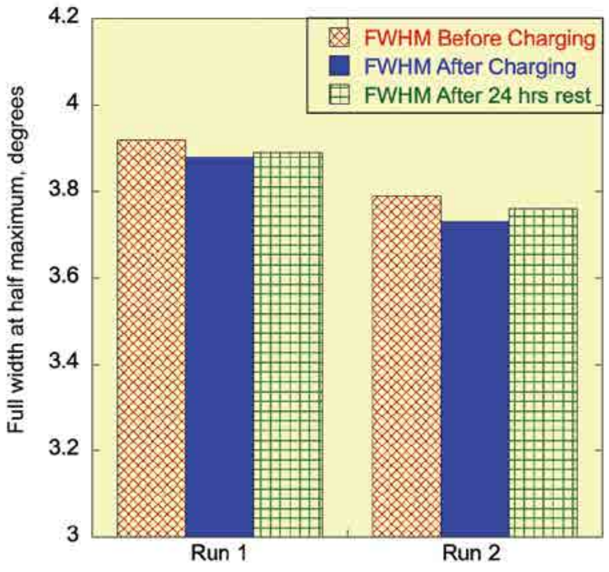

Figure Four

To explain this phenomena, we examined the full width at half maximum (FWHM) of the x-ray measurements. The FWHM increases with increasing dislocation content in metals. As shown in Figure 4, the FWHM decreased slightly after charging, which strongly suggests that solute H was interacting with the dislocations created from the peening process, and likely causing those dislocations to re-arrange and annihilate. The Hydrogen Enhanced Localized Plasticity (HELP) model of hydrogen embrittlement [5], where solute hydrogen increases the mobility of some dislocations and enhances planar slip, could decrease the dislocation content in the surface (where plasticity was the highest after peening). This gradient in plastic deformation and hydrogen content likely could also be responsible for the semi-permanent nature of the change in residual stresses in peened samples after hydrogen charging.

CONCLUSIONS

Hydrogen is, and will continue to be, prevalent in many engineering systems where peened components are used to enhance the surface properties of materials. In medium carbon steels that have been shot peened, we demonstrated that hydrogen which enters the steel can reduce compressive stresses in the sample, and that these effects are not completely reversible (i.e., when the hydrogen is removed a fraction of the reduction in stress remains). Therefore, peened parts being placed in hydrogen containing environments may suffer a degradation in their compressive stresses imposed from peening. Further work by researchers in Purdue's Center for Surface Engineering and Enhancement will continue to explore the interaction between hydrogen environments and peened materials.

ACKNOWLEDGEMENTS

This work was supported by the Purdue University Center for Surface Engineering and Enhancement, an industry funded consortium. In particular, the support of Jack Champaigne of Electronics Inc. in South Bend, Indiana and Jim Whalen of Progressive Surface in Grand Rapids, Michigan is greatly appreciated. We are grateful for the assistance with initial stress measurements and sample preparation from Nathan Lieu, Aleena Masaeng, and Matthew Wright, undergraduate students at Purdue University.

REFERENCES

1. A. Dreano, M. Alnajjar, F. Salvatore, J. Rech, C. Bosch, K. Wolski, G. Kermouche, and F. Christien, "Effect of ball-burnishing on hydrogen-assisted cracking of a martensitic stainless steel," Int J Hydrogen Energy, vol. 47, pp. 39654–39665, 2022, doi: 10.1016/j.ijhydene.2022.09.110.
2. Y. Wang, X. Wu, and W. Wu, "Effect of α martensite content induced by tensile plastic prestrain on hydrogen transport and hydrogen embrittlement of 304L austenitic stainless steel," Metals, vol. 8, pp. 1–23, 2018, doi: 10.3390/met8090660.
3. X. Li, J. Zhang, Y. Wang, M. Ma, S. Shen, and X. Song, "The dual role of shot peening in hydrogen-assisted cracking of PSB1080 high strength steel," Mater Des, vol. 110, pp. 602–615, 2016, doi: 10.1016/j.matdes.2016.07.121.
4. K. Makoto, U. Wataru, and Y. Satoshi, "Improved hydrogen embrittlement resistance of steel by shot peening and subsequent low-temperature annealing," ISIJ International, vol. 61, pp. 1159–1169, 2021, doi: 10.2355/isijinternational.ISIJINT-2020-463.
5. H. K. Birnbaum and P. Sofronis, "Hydrogen-enhanced localized plasticity-a mechanism for hydrogen-related fracture." Materials Science and Engineering, vol. 176, pp. 191–202, 1994.

Jack Champaigne Receives the Purdue College of Engineering 2025 Distinguished Engineering Alumni Award

The Distinguished Engineering Alumni/Alumnae Award for the Purdue College of Engineering is presented to men and women who have distinguished themselves in any field in ways that reflect favorably on Purdue University, the engineering profession, or society in general.

These alumni are engaged in engineering work and their record of accomplishments is indicated by their growth into positions of increasing responsibility.

This award is the highest honor bestowed by the College to its alumni and it recognizes those who have made outstanding contributions within their fields.

To mark this occasion, a celebration is set for Thursday, April 10, 2025, at 6:00 p.m. ●