AerMet® 100 alloy is a secondary hardening martensitic steel that combines high hardness and strength with exceptional ductility and toughness\(^1\). This modern steel is used in ultra-high strength applications and must be protected against corrosion. This is done by electroplating a 5-25 µm thick protective Cd-layer on the steel surface. Unfortunately, during the electroplating process, hydrogen co-deposits on the steel surface and diffuses into the steel. Even in very low concentrations in the bulk lattice, H can migrate to areas of high triaxial stresses, thereby magnifying its effect and causing time dependent hydrogen embrittlement\(^2\).

The AerMet® 100 microstructure contains many features that are known to trap H in steel; such as dislocations, carbides, martensite lath interfaces, solutes and prior-\(\gamma\) grain boundaries. Trapping at such features can significantly affect the internal hydrogen embrittlement (IHE) behavior by complex mechanisms. For example, a distribution of strong irreversible H traps may prevent H from partitioning to lower interaction energy sites, such as prior-\(\gamma\) grain boundaries and lath martensite interfaces, that are susceptible to low-stress intensity H-induced fracture and increase the resistance to HE\(^3,4,5\). In contrast, a distribution of weak reversible H traps may provide a reservoir of diffusible (mobile) H that can repartition to and within the fracture process zone to sites susceptible to H-induced cracking, thus worsening the fracture process\(^6,7\).

Earlier studies have shown that plane strain elastic-plastic toughness decreased drastically from 140 MPa√m to less than 20 MPa√m due to hydrogen precharging in alkaline Ca(OH)\(_2\) and slow rate loading (Figure 1). The fracture mode changed from microvoid coalescence for the uncharged case to brittle cleavage-like transgranular fracture for diffusible hydrogen concentrations between 2 to 8 wppm (Figure 2)\(^8\). This H-induced cracking of AerMet® 100 at \(K_{TH}\) values less than 20 MPa√m is unique in comparison to HE in similar strength steels. Low \(K_{TH}\) values are typically associated with intergranular fracture, while transgranular H-induced cracking generally accompanies much higher \(K_{TH}\). This is ascribed to a synergistic effect of H and impurities segregated to grain boundaries, decreasing the grain boundary strength\(^9\). The low impurity levels of AerMet® 100 have essentially eliminated H-induced intergranular cracking. Only limited areas of prior austenite grain boundary cracking occurred in AerMet® 100 for the higher total H concentration levels. Instead severe
brittle transgranular fracture due to IHE in AerMet® 100 results from stress-induced hydrogen repartitioning to potential fracture sites during loading\(^8\).

Current research has shown that the hydrogen embrittlement of H charged, un-plated AerMet® 100 may be reversed and the recovery of the original fracture toughness value is possible if baked at elevated temperatures such as 190 °C if the enough time is given. Baking greatly effects the diffusible H concentrations of charged specimens. For example; baking the H charged (\(C_{\text{H Diff}}=7.5\) wppm) specimens for three days at room temperature reduced the \(C_{\text{H Diff}}\) value to 0.34 wppm, by 95 percent, and elevated temperature baking at 200 °C for 2.3 hours eliminated the diffusible H in the steel. Despite the great reduction of the lattice and the weakly trapped hydrogen, aprox. 40 percent of the total H remained in the steel which resides in the strong H trap sites\(^12\). In order to find out whether such trapped hydrogen effects IHE or not, \(K_{\text{IC}}\) was determined for a charged and for a charged/baked specimens. Figure 3 shows the load vs CMOD data for the charged and charged/baked CT specimens. H charged (\(\eta_{\text{chg}}=-0.3\) V [vs. Hg/Hg\(_2\)SO\(_4\)] and \(C_{\text{H Diff}}=4.0\) wppm) specimen exhibited severe hydrogen embrittlement with threshold stress intensity, \(K_{\text{TH}}=15.9\) MPa√m. Baking the identically charged specimen at 190 °C for 24 hours was sufficient to eliminate all the diffusible hydrogen which reversed the HE and restored the fracture toughness of \(K_{\text{IC}}=123\) MPa√m which is close to or at the level of the fracture resistance of un-charged AerMet® 100. However, these measurements must be repeated for Cd-Plated specimens.

Cd-plated AerMet® 100, like other ultra-high strength steels, is baked at 190 °C for 5 to 24 hours to remove the dissolved hydrogen after electroplating. The effectiveness of this standard post-plating thermal treatment is questionable, particularly for AerMet® 100. High hydrogen solubility in Cd, relative to that in Fe, allows the electroplated Cd-layer to act as a H source during the initial stage of baking, and consequently, the H concentration in the steel substrate may increase\(^10\). Furthermore, because H diffusivity in Cd is much slower than that in steel, the Cd-layer act as a diffusion barrier to H loss during baking and significant concentrations of dissolved hydrogen may remain in the steel, even after heating times of 100 hours\(^11\). Moreover, the diffusivity in AerMet® 100 is slower than in many quenched and tempered steels such as AISI 4130 and the H trap capacity is greater. These uncertainties in the post-plating heat treatment process causes IHE to be a concern in Cd-plated AerMet® 100 components.

The objectives of this research are to quantitatively characterize and understand the effects of hydrogen that is introduced during the cadmium plating of AerMet® 100 on the mechanical properties and investigate the effectiveness of post-plating baking treatment on the removal of diffusible and trapped hydrogen content. For these purposes, Barnacle Electrode method and LECO/ASTM 1447 hot extraction method are being used to quantify the diffusible H concentrations and the total H concentrations respectively. Investigation of the retained hydrogen as a function of trap state in the Cd-plated AerMet® 100 specimens is being accomplished using the Thermal Desorption Spectroscopy. As a future work, experiments are needed using
the elastic-plastic fracture mechanics test method to determine the effect of baking on the fracture toughness of Cd-plated specimens as a function of baking time and temperature and to correlate to the remaining diffusible and trapped hydrogen.

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Figure 1. Threshold stress intensity for hydrogen embrittlement, $K_{TH}$, at various (a) diffusible H concentrations and (b) total H concentrations. A significant decrease in $K_{TH}$ was observed at all H concentrations dissolved in peak aged AerMet® 100.
Figure 2. Scanning electron images of the fracture surfaces of AerMet® 100 specimens with a diffusible H concentration of (a) 0 wppm and (b) 7.8 wppm. The fracture surface is characterized by ductile-microvoid features in the absence of H (a) and by brittle transgranular features with precharged H (b). Crack growth in both images was from top to bottom.
Figure 3. Load versus CMOD data for the charged and charged/baked specimens. Charging was done in saturated Ca(OH)$_2$ at the charging overpotential of –0.30 V at 60 °C for 20 days.