

# Hydrogen Diffusion and Trapping in Ultrahigh-Strength AerMet<sup>®</sup> 100

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AerMet<sup>®</sup> 100 is a new generation ultrahigh-strength steel (UHSS) and is currently specified for manufacturing important aircraft parts such as landing gears. As a UHSS, AerMet<sup>®</sup> 100 is susceptible to internal hydrogen embrittlement (IHE) and the mechanisms are complicated due to the trapping - H transport interactions, given the fine-scale microstructural features serving as potential trap sites (dislocations, precipitates, undissolved metal carbides, martensite lath interfaces, etc.). The present investigation is aimed at understanding the role of traps as storage sites for H that could repartition to crack tips, with emphasis on trap state analyses, binding energy estimations and the association with specific microstructural features of AerMet<sup>®</sup> 100. It is also sought to understand residual trap occupancy as a result of baking condition as well as the impact of such residual H on susceptibility to IHE.

H diffusion and trapping behavior in ultra-high strength AerMet<sup>®</sup> 100 is characterized after various electrochemical charging and baking conditions using thermal desorption spectroscopy (TDS). Due to heavy trapping, the apparent H diffusivity  $D_{app}$  ( $< 3 \times 10^{-8}$  cm<sup>2</sup>/s at 23°C) is over 10-fold less than values typical of tempered martensitic steels such as AISI 4130. The temperature dependence of  $D_{app}$  ranging from 23°C to 200°C results in activation energy for diffusion ( $E_m^{app}$ ) of 17.7 kJ/mol and 18.0 kJ/mol, for specimens charged at overpotentials of -1.17V and -0.62V, respectively.  $D_{app}$  decreases with decreasing diffusible H concentration from less severe charging or increased baking, indicating H-concentration dependent diffusion behavior. The ramp TDS experiments identify three major desorption peaks, denoted peak 1, peak 2 and peak 3, in association with three distinct trap states (Fig. 1). Analysis of H binding energies suggests that both reversible and irreversible H-traps are responsible for the slow H diffusivity and high H uptake capacity observed. M<sub>2</sub>C precipitates are identified to be the main source of reversible H trap sites (with binding energies,  $E_b$ , of 11.4-11.6±0.2 kJ/mol), together with the portion of Cr and Mo atoms that are not consumed in carbides (Fig. 2). This low-energy reversible H trap sites may also include dislocations. Irreversible trap sites (with  $E_b$  of 61.3-62.2±0.3 kJ/mol) may include mixed dislocation cores and various interfaces including martensitic and autenitic boundaries and grain boundaries (Fig. 2). Undissolved metal carbides and highly disorientated grain boundaries may irreversibly trap H with the highest binding energy level (with  $E_b$  of 89.1-89.9±0.3 kJ/mol, Fig. 2).

Baking at room temperature and 190-200°C removes, to varying degrees, diffusible and reversibly-trapped H ( $E_b = 11.4-11.6 \pm 0.2$  kJ/mol). For a plate specimen of about 0.5 mm thick charged to ~ 30 wppm H, baking at 190°C for about 2 h essentially removes diffusible and reversibly-trapped H from bare AerMet<sup>®</sup> 100 (Fig. 3). However, considerable amount of H is still trapped in irreversible trap sites ( $E_b \geq 61.3-62.2 \pm 0.3$  kJ/mol), even after baking at 190°C for 200 h (Fig. 3). Baking at 300-350 °C can effectively drive out H trapped in the irreversible trap sites associated with peak 2, with negligible change in the microstructure of the peak-hardened alloy (Fig. 4). In contrast, baking at 400 °C and up not only leads to strengthening of the H traps originally associated with peak 3 found in the as-charged alloy (Fig. 4), but it also tends to sacrifice the desired mechanical performance due to the microstructural modification caused by the high temperature baking.

As H-trap binding energy data are of key importance in quantifying the trap states, the present results establish a solid basis in understanding the fundamental trapping processes in AerMet<sup>®</sup> 100. In addition, the trapping-affected slow H diffusivity, high H uptake and residual trapped H are important issues to consider regarding the susceptibility of AerMet<sup>®</sup> 100 to IHE after Cd-plating and subsequent baking. The information generated in this work provides a basic insight into the thermal conditions required for the removal of H from various trap states in the bare alloy. It also serves as a foundation for understanding H detrapping from Cd-plated AerMet<sup>®</sup> 100.

*Acknowledgment* — Financial Support from the Office of Naval Research (Grant Number N00014-98-1-0740) under the direction of contract monitor Dr. A. John Sedriks is gratefully acknowledged. Thanks are also due to contributions of electrochemical instrumentation by Perkin Elmer Corporation and Scribner Associates, Inc.

#### Related Publications:

1. R.L.S. Thomas, D. Li, R.P. Gangloff and J.R. Scully, “Trap-Governed Hydrogen Diffusivity and Uptake Capacity in Ultrahigh-Strength AerMet<sup>®</sup> 100 Steel”, *Metallurgical and Materials Transactions - A*, 2002, vol.33A, pp. 1991-2003.
2. R.L.S. Thomas, J.R. Scully and R.P. Gangloff, “Internal Hydrogen Embrittlement of Ultrahigh-Strength AerMet<sup>®</sup> 100 Steel”, *Metallurgical and Materials Transactions - A*, 2002, vol.33A, in press.

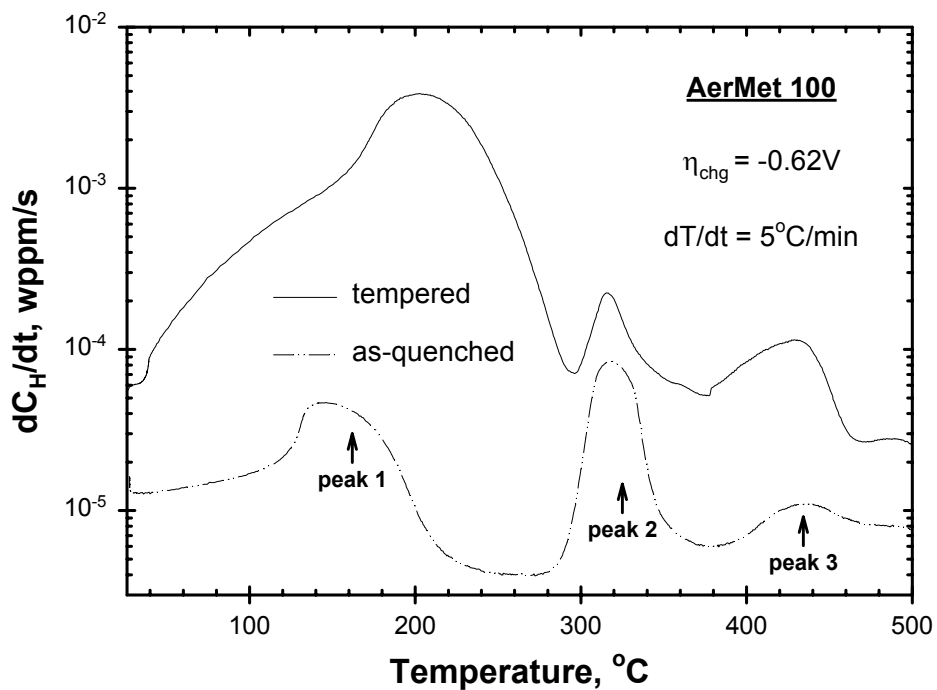


Fig. 1. H desorption rate ( $dC_H/dt$ ) versus temperature curves for as-quenched and tempered specimens charged at overpotential ( $\eta_{\text{chg}}$ ) of -0.62V and TDS tested at a heating rate ( $dT/dt$ ) of 5  $^\circ\text{C/min}$ .

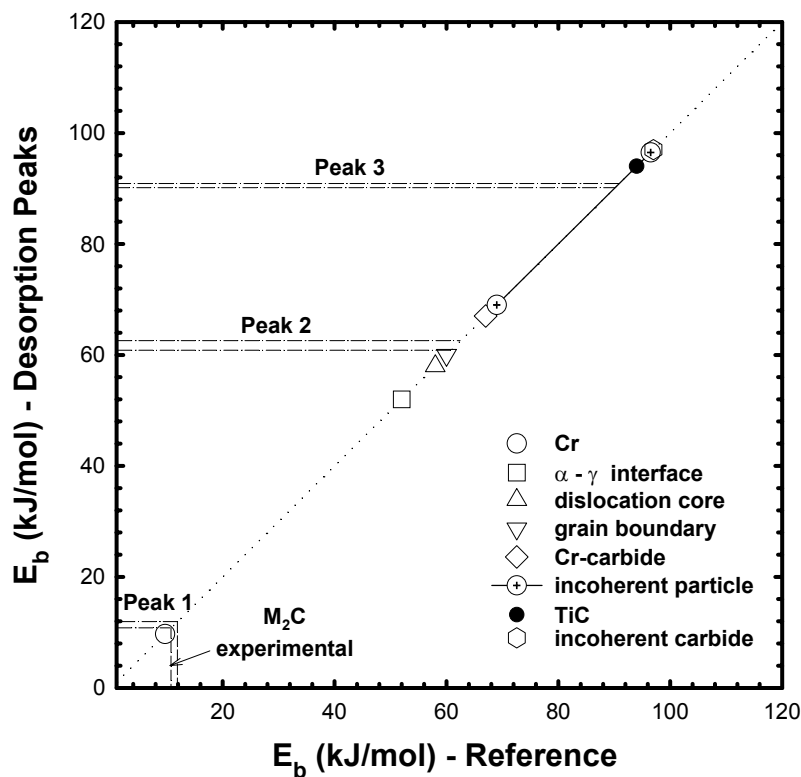


Fig. 2. H-trap binding energies ( $E_b$ ) obtained from desorption peaks by TDS experiments in comparison with established literature data (reference) to match microstructural features.

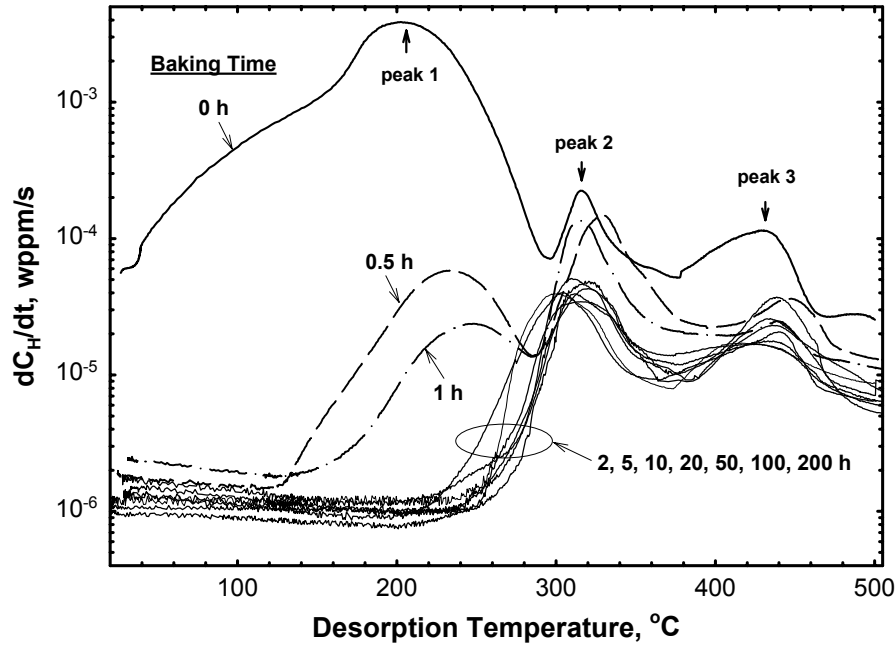


Fig. 3. H desorption rate ( $dC_H/dt$ ) versus temperature relationship obtained by TDS tests at a heating rate of  $5^\circ\text{C}/\text{min}$  for specimens previously charged at  $\eta_{\text{chg}} = -0.62\text{ V}$  ( $60^\circ\text{C}$ ) and baked at  $190^\circ\text{C}$  for various lengths of time indicated beside each curve(s), in comparison with the as-charged state (0 h).

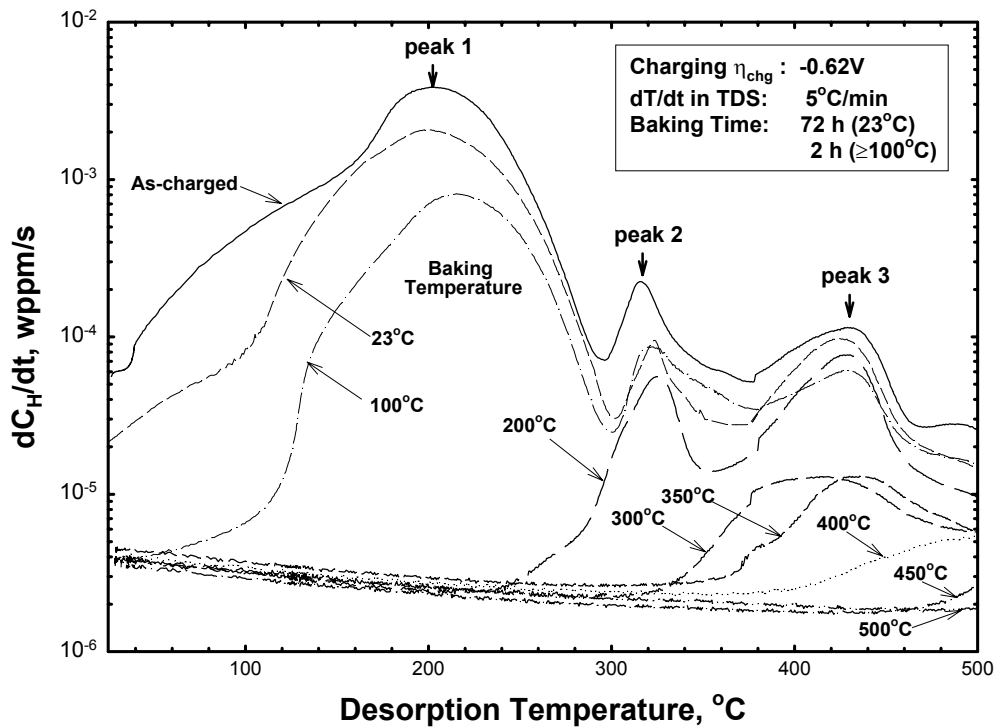


Fig. 4. H desorption rate ( $dC_H/dt$ ) versus temperature curves obtained by TDS tests at a heating rate of  $5^\circ\text{C}/\text{min}$  for specimens previously charged at  $\eta_{\text{chg}} = -0.62\text{ V}$  ( $60^\circ\text{C}$ ) and baked at various temperatures indicated beside each curve, in comparison with the as-charged state. Baking time was 72 h for  $23^\circ\text{C}$  baking and 2 h for elevated temperature baking.