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Nanoscale Microstructure Effects on Hydrogen Behavior in Rapidly Solidified Aluminum Alloys

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Abstract. The present work summarizes recent progress in the investigation of nanoscale microstructure effects on hydrogen behavior in rapidly solidified aluminum alloys foils produced at exceptionally high cooling rates. We focus here on the potential of modification of hydrogen desorption kinetics in respect to weak and strong trapping sites that could serve as hydrogen sinks in Al materials. It is shown that it is important to elucidate the surface microstructure of the Al alloy foils at the submicrometer scale because rapidly solidified microstructural features affect hydrogen trapping at nanostructured defects. We discuss the profound influence of solute atoms on hydrogen–lattice defect interactions in the alloys. with emphasis on role of vacancies in hydrogen evolution; both rapidly solidified pure Al and conventionally processed aluminum samples are considered.

A key breakthrough in hydrogen embrittlement (HE) studies in Al-based systems is recognition of the need to perform nanoscale and submicrometer characterization of the material's local composition and structure in coordination with hydrogen measurements. While embrittlement mechanisms remain controversial with regard to Al alloys of commercial interest as liner materials for efficient storage of compressed hydrogen gas [1], it should be highlighted that, to date, hydrogen behavior in Al materials prepared at exceptionally high cooling rates is not well understood. Therefore, the emergence of advanced processing techniques for rapidly solidified Al has prompted studies to develop a deeper mechanistic understanding of hydrogen/microstructure interactions in high-strength Al alloys, with a view to understanding the HE susceptibility of Al alloys intended for hydrogen-based energy technologies.

Here we review our recent results on diffusion and trapping of hydrogen, with emphasis on nanoscale microstructural evolution in rapidly solidified (RS) Al-based alloys. We use synchrotron radiation–based scanning photoelectron microscopy (SR-SPEM) and ion beam analysis (IBA) techniques in a complementary way to obtain direct observations of the microstructure evolution and depth profiling of the elemental composition with nanoscale precision. The SPEM measurements were carried out at the ESCA microscopy beamline at the third-generation Elettra Synchrotron Light Source. The IBA experiments were carried out using a MeV helium ion beam from a van de Graaff accelerator. Thermal desorption spectroscopy (TDS) and thermal desorption analysis (TDA) were employed to study hydrogen trapping behavior in the specimens regarding alloy composition in vacuum and air, respectively.

For the first time, we found a modification of hydrogen behavior in respect to benign traps that could serve as hydrogen sinks in Al materials: the TDS spectra show a prominent difference between RS pure Al and traditionally processed Al samples (Fig. 1a). The hydrogen behavior in RS Al alloys is strongly affected by microstructural features available because of rapid solidification and represents the trapping of hydrogen in at least at four states, associated with alloying elemental atoms, vacancies, dislocations, and voids [2, 3] (Fig. 1b). The SR-SPEM analysis (Fig. 1c) accompanied by IBA showed a nonuniform dope depth distribution from the surface to the bulk of RS foils depending on alloying element. Revealed microstructural solute segregation phenomenon [4, 5] showed the important role of solute in H/microstructure interactions in RS Al-based alloys because it is suggested to account for the observed drastic decrease of hydrogen content trapped by quenched-in vacancies in alloys compared with pure Al. The alloying elements are demonstrated to be responsible for a strong tendency for hydrogen to be trapped by dislocations as well as by alloying element atoms in substitutional lattice sites. On the basis of obtained patterns of hydrogen evolution as well as dope depth distribution behavior in RS foils, we can conclude that the role of lattice

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defects in solute/microstructure interactions represents a key contribution to the understanding of H trapping in RS Al alloys.

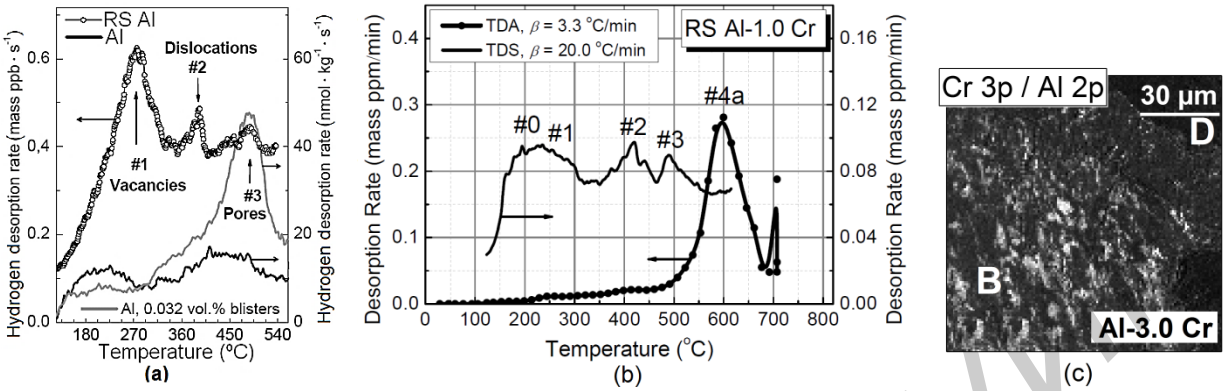

FIGURE 1. Hydrogen and solute trapping behavior of Al-based foils: (a) TDS spectra for RS pure Al and traditionally processed samples [2]; (b) TDA and TDS spectra for RS Al-Cr alloy [3] and (c) SR-SPEM micrographs representing the proportion of Cr presented in Al matrix of RS foil surface [4].

Overall, our work demonstrates that hydrogen behavior in Al and its alloys depends significantly on microstructural features that are available because of rapid solidification at exceptionally high cooling rates. It is noteworthy that there is a lack of SR-SPEM studies on solute surface segregation in microcrystalline RS Al alloys. It is therefore important to consider that the characterization of RS Al alloys on the nanoscale using SR-SPEM leads to a deeper understanding of hydrogen/microstructure interactions in RS materials. From the patterns of hydrogen trapping behavior observed in RS pure Al and its alloys and through accompanying characterization of their local composition and structure at the nanometer scale, there appears to be a need for further work that will necessitate a multiscale framework to clarify details of complex hydrogen interactions and evolution in modified RS microstructures and improve resistance of Al-based alloys to HE.

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