Technical Reference on Hydrogen Compatibility of Materials

Aluminum Alloys:
Heat-Treatable Alloys, 2XXX-series (code 3210)

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1. General

It is generally accepted that a metal must adsorb hydrogen before the hydrogen can degrade the properties of the metal. The thermodynamics and kinetics of the interactions between gaseous hydrogen and aluminum alloys are not well understood. Therefore, the effects of gaseous hydrogen on fracture in aluminum alloys has not been adequately addressed in the literature.

Despite an incomplete understanding of the fundamental thermodynamics and kinetics of hydrogen-aluminum interactions, all of the available data suggest that the structural properties of aluminum alloys are not affected by gaseous hydrogen if moisture is absent [1, 2]. Studies of the micromechanics of deformation in aluminum, on the other hand, show that deformation is strongly affected by hydrogen [3, 4], demonstrating that hydrogen may affect the mechanical properties of aluminum alloys. Indeed, aluminum alloys can be susceptible to stress corrosion cracking [5, 6], for which hydrogen-assisted fracture is one mechanistic interpretation of property degradation [1, 5, 7].

More work is necessary to determine the limiting behavior of 2XXX-series in gaseous hydrogen. Nevertheless, the available data from the stress-corrosion-cracking literature appears to provide a more conservative assessment of hydrogen-assisted fracture in aluminum alloys than gaseous hydrogen exposures.

1.1 Composition and microstructure

The Aluminum Association (AA) designations are typically used for aluminum alloys and the materials definitions are provided in the AMS specifications (Aerospace Material Specification, also called SAE-AMS). The 2XXX-series alloys are the aluminum-copper, precipitation-strengthening aluminum alloys, although engineering alloys include controlled amounts of other transition metals and silicon. Several common varieties are given in Table 1.1.1.

The alloy temper (i.e., specific heat treatment) is specified after the AA designation, such as 2014-T6. Mill tempers often include stress relief and may include several numbers, such as T6511. The T6 temper represents the peak-aged condition and is the most common for the 2XXX-series alloys. The T8 tempers are strain-hardened, then precipitation-strengthened. Common tempers for aluminum alloys are specified in AMS 2770 thru 2772.

1.2 Common designations

UNS A92014 (2014), UNS A92024 (2024), UNS A92219 (2219), UNS A92224 (2224)

2. Permeability, Diffusivity and Solubility

The solubility and diffusivity of hydrogen in pure aluminum are reviewed in Refs. [8, 9]; little data for engineering alloys is reported in the literature. The data for pure aluminum is summarized in the section of this Technical Reference on pure aluminum alloys.

3. Mechanical Properties: Effects of Gaseous Hydrogen

3.1 Tensile properties

3.1.1 Smooth tensile properties

There are few published data for 2XXX-series aluminum alloys in gaseous hydrogen. The limited data [10] show a slight increase in ductility for aluminum alloys when tested in high-pressure gas compared to tests in air, Table 3.1.1.1. The apparent improvement in ductility is likely related to removal of the environmental condition associated with atmospheric moisture.

3.1.2 Notched tensile properties

No known published data in hydrogen gas.

3.2 Fracture mechanics

The fracture toughness (K_{IC}) and threshold stress intensity factor (K_{TH}) of 2219-T87 aluminum are reported by Walter and Chandler in 34.5 MPa gaseous hydrogen and helium at room temperature and temperature of 144 K [11]. Their 2219-T87 material was obtained as plate with a yield strength of 390 MPa. They found essentially no difference in values of fracture reisstance measured in helium and hydrogen: both K_{IC} and K_{TH} values are reported to be about 30 MPa $m^{1/2}$ at room temperature, and about 40 MPa $m^{1/2}$ at 144 K.

3.3 Fatigue

No known published data in hydrogen gas.

3.4 Creep

No known published data in hydrogen gas.

3.5 Impact

No known published data in hydrogen gas.

3.6 Disk rupture testing

No known published data in hydrogen gas.

4. Fabrication

4.1 Primary processing

Relatively large hydrogen contents in aluminum alloys can result from casting processes due to the high solubility of hydrogen in liquid aluminum [12]; this residual hydrogen can be much larger than dissolved from exposure to high-pressure gaseous hydrogen near room temperature. There is a significant body of literature that addresses this issue for castings [13].

4.2 Heat treatment

Vacancies appear to play an important role in trapping and transport of hydrogen in aluminum alloys [8, 9], therefore the high concentrations of vacancies associated with tempering are likely to have a substantial effect on hydrogen transport in precipitation-strengthened aluminum alloys. It is unclear, however, if trapped hydrogen plays a significant role on the micromechanisms of hydrogen-assisted fracture in aluminum alloy exposed to gaseous hydrogen.

5. References

1. MO Speidel. Hydrogen Embrittlement and Stress Corrosion Cracking of Aluminum Alloys. in: R Gibala and RF Hehemann, editors. Hydrogen Embrittlement and Stress Corrosion Cracking. Metals Park OH: American Society for Metals (1984) p. 271-296.
2. PM Ordin. Safety Standard for Hydrogen and Hydrogen Systems: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation. Office of Safety and Mission Assurance, National Aeronautics and Space Administration, Washington DC (1997).
3. GM Bond, IM Robertson and HK Birnbaum. Effects of hydrogen on deformation and fracture processes in high-purity aluminum. Acta Metall 36 (1988) 2193-2197.
4. PJ Ferreira, IM Robertson and HK Birnbaum. Hydrogen effects on the character of dislocations in high-purity aluminum. Acta Mater 47 (1999) 2991-2998.
5. GA Young and JR Scully. The effects of test temperature, temper, and alloyed copper on the hydrogen-controlled crack growth rate of an Al-Zn-Mg-(Cu) Alloy. Metall Mater Trans 33A (2002).
6. RP Gangloff. Hydrogen assisted fracture of high strength alloys. in: I Milne, RO Ritchie and B Karihaloo, editors. Comprehensive Structural Integrity. 6. New York NY: Elsevier Science (2003).
7. H Vogt and MO Speidel. Stress corrosion cracking of two aluminum alloys: a comparison between experimental observations and data based on modelling. Corros Sci 40 (1998) 251-270.
8. GA Young and JR Scully. The diffusion and trapping of hydrogen in high purity aluminum. Acta Mater 46 (1998) 6337-6349.
9. JR Scully, GA Young and SW Smith. Hydrogen solubility, diffusion and trapping in high purity aluminum and selected Al-base alloys. Materials Science Forum 331-337 (2000) 1583-1600.
10. MR Louthan and G Caskey. Hydrogen Transport and Embrittlement in Structural Metals. Int J Hydrogen Energy 1 (1976) 291-305.
11. RJ Walter and WT Chandler. Influence of Gaseous Hydrogen on Metals: Final Report. Rocketdyne for the National Aeronautics and Space Administration, Canoga Park CA (Oct 1973).
12. DEJ Talbot. Effects of hydrogen in aluminum, magnesium, copper, and their alloys. International Metallurgical Reviews 20 (1975) 166-184.

13. PN Anyalebechi. Techniques for determination of the hydrogen content in aluminum and its alloys. in: Proceedings of the 120th TMS Annual Meeting: Light Metals, 1991, New Orleans LA. TMS: Warrendale PA p. 1025-1046.
14. ASTM. ASTM DS-56H, Metals and Alloys in the UNIFIED NUMBERING SYSTEM (SAE HS-1086 OCT01). 2001.

Table 1.1.1. Compositional ranges (wt%) of several common 2XXX-series aluminum alloys [14]; additional and modified requirements are common for specific applications.

UNS No	Aluminum Association Designation	Al	Cu	Mg	Mn	Zn	Cr	Ti	V	Zr	Si	Fe
A92014	2014	Bal	5.0 3.9	0.80 0.20	1.2 0.40	0.25 max	0.10 max	0.15 max	—	—	1.2 0.50	0.70 max
A92024	2024	Bal	4.9 3.8	1.8 1.2	0.90 0.30	0.25 max	0.10 max	0.15 max	—	—	0.50 max	0.50 max
A92224	2224	Bal	4.4 3.8	1.8 1.2	0.90 0.30	0.25 max	0.10 max	0.15 max	—	—	0.12 max	0.15 max
A92219	2219	Bal	6.8 5.8	0.02 max	0.40 0.20	0.10 max	—	0.10 0.02	0.10 0.25	0.05 0.15	0.20 max	0.30 max

Table 3.1.1.1. Smooth tensile properties of 2XXX-series aluminum alloys tested at room temperature in high-pressure helium and hydrogen gas.

Material	Thermal precharging	Test environment	Strain rate (s^{-1})	S_y (MPa)	S_u (MPa)	El_u (%)	El_t (%)	RA (%)	Ref.
2011	None	Air	—	269	338	—	17	48	[10]
	None	69 MPa He		227	296	—	18	57	
	None	69 MPa H_2		220	296	—	17	58	
2024	None	Air	—	358	489	—	15	33	[10]
	None	69 MPa He		324	441	—	19	36	
	None	69 MPa H_2		310	427	—	18	35	