Technical Reference on Hydrogen Compatibility of Materials

Aluminum Alloys:
Heat-Treatable Alloys, 7XXX-series (code 3230)

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1. General

The 7XXX-series aluminum alloys are attractive for structural applications, since these alloys can be strengthened through heat treatment. The 7XXX alloys have elements such as Zn, Mg, and Cu that form precipitates in the aluminum matrix when the alloys are heat treated. These precipitates are the source of strengthening in the 7XXX alloys.

It is generally accepted that atomic hydrogen must dissolve in a metal in order to degrade the mechanical 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 of aluminum alloys have not been adequately explored in the literature.

Despite an incomplete understanding of the fundamental thermodynamics and kinetics of hydrogen gas-aluminum interactions, all of the available data suggest that the mechanical properties of aluminum alloys are not degraded in dry gaseous hydrogen [1, 2]. However, studies of stress-corrosion cracking of aluminum alloys have implicated environmental hydrogen in the cracking mechanism [2-4], indicating that aluminum alloys are not inherently immune to hydrogen-assisted fracture. While stress-corrosion cracking data may provide a conservative assessment of hydrogen-assisted fracture of aluminum alloys, more work is necessary to evaluate the realistic performance of 7XXX alloys in gaseous hydrogen.

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 alloy temper (i.e., heat treatment process) is specified after the AA designation, such as 7475-T7351. Common tempers for aluminum alloys are specified in AMS 2770 thru 2772.

Data on mechanical properties for 7XXX aluminum in gaseous hydrogen were identified for two alloys: 7039 and 7475. The alloy composition specifications for these two alloys are provided in Table 1.1.1.

1.2 Common designations

UNS A97039 (7039), UNS A97475 (7475)

2. Permeability, Diffusivity and Solubility

The solubility and diffusivity of hydrogen in pure aluminum are reviewed in Refs. [5, 6]; limited data for structural aluminum alloys are reported in the literature. The data for pure aluminum are summarized in this section of the Technical Reference (code 3101).

3. Mechanical Properties: Effects of Gaseous Hydrogen

3.1 Tensile properties

3.1.1 Smooth tensile properties

Limited data for 7XXX aluminum show that the tensile properties of these alloys are not affected by gaseous hydrogen, Table 3.1.1.1. This result was independent of how the materials were tested, i.e., concurrently strained and exposed to hydrogen gas or strained in air after long-term hydrogen exposure. It is noted that the properties in Table 3.1.1.1 are for a single alloy, 7039, but the test methods were applied to materials having different strength levels. The heat treatments for the two 7039 materials were not reported [7], but it is likely that the low-strength material was not precipitation hardened.

3.1.2 Notched tensile properties

No known published data in hydrogen gas.

3.2 Fracture mechanics

Sustained-load cracking tests conducted on 7XXX aluminum alloys in high-pressure gaseous hydrogen did not reveal any hydrogen-induced subcritical crack extension. Table 3.2.1 summarizes details of the testing on a 7475-T7351 alloy [8]. The wedge-opening load (WOL) specimens had two different orientations relative to the aluminum plate dimensions: tensile loading parallel to the longitudinal direction with cracking parallel to the transverse direction (LT orientation) and tensile loading parallel to the thickness dimension with cracking parallel to the transverse direction (ST orientation). No cracking was detected in the aluminum alloys during exposure to 207 MPa hydrogen gas for 5000 hrs at the prescribed initial stress-intensity factor levels.

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 [9]; this residual hydrogen content can be much larger than the amount dissolved from exposure to high-pressure gaseous hydrogen near room temperature. There is a significant body of literature that addresses this issue for castings [10].

4.2 Heat treatment

Vacancies appear to play an important role in trapping and transport of hydrogen in aluminum alloys [5, 6], therefore the high concentrations of excess vacancies resulting from heat treatment 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 in enabling hydrogen-assisted fracture in aluminum alloys exposed to gaseous hydrogen.

5. **References**

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Table 1.1.1. Allowable composition ranges (wt%) for 7XXX-series aluminum alloys in hydrogen compatibility studies [11].

UNS No.	Aluminum Association Designation	Al	Cu	Mg	Mn	Zn	Cr	Ti	Si	Fe
A97039	7039	Bal	0.10 max	2.3 3.3	0.10 0.40	3.5 4.5	0.15 0.25	0.10 max	0.30 max	0.40 max
A97475	7475	Bal	1.2 1.9	1.9 2.6	0.06 max	5.2 6.2	0.18 0.25	0.06 max	0.10 max	0.12 max

Table 3.1.1.1. Smooth tensile properties of 7XXX-series aluminum alloys tested at room temperature in hydrogen gas or tested in air after long-term hydrogen exposure. Properties in air and/or helium gas are included for comparison.

Material	Thermal precharging	Test environment	Strain rate (s^{-1})	S_y (MPa)	S_u (MPa)	El_u (%)	El_t (%)	RA (%)	Ref.
7039	None	Air	—	152	179	—	14	80	[7]
	None	69 MPa He		124	138	—	14	85	
	None	69 MPa H_2		117	138	—	14	86	
7039	None	Air	—	303	379	—	13	44	[7]
	(1)	Air		310	372	—	14	45	

(1) 69 MPa H_2, 343K, 524 days

Table 3.2.1. Sustained-load cracking results for 7XXX-series aluminum alloys in high-pressure gaseous hydrogen at room temperature.

Material	S_y† (MPa)	RA† (%)	K_{Ic}† (MPa ·$m^{1/2}$)	Test Environment	K_{TH} (MPa ·$m^{1/2}$)	Ref.
7475-T7351 LT orientation	445	38	—	207 MPa H_2	NCP 40*	[8]
7475-T7351 ST orientation	432	26	—	207 MPa H_2	NCP 30*	[8]

NCP = no crack propagation at reported applied K level
†properties measured in air
*5000 hr test duration