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An investigation of mechanical degradation of AlMg1SiCu aluminum alloy by hydrogen

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Abstract

The mechanical degradation of AlMg1SiCu aluminum alloy by hydrogen was investigated using experiments conducted on specimens that were hydrogen charged under different cathodic charging conditions. Cathodic hydrogen charging was found to reduce the ultimate tensile strength, yield strength and ductility of aluminum alloy. These parameters decreased with increasing cathodic current density and charging time. However, it was found that cathodic hydrogen charging for longer time resulted in more reduction of tensile properties than that at higher current density. Moreover, mixed mode of hydrogen cracking (i.e. intergranular and transgranular) as well as gas bubbles were observed during first charging condition while only intergranular cracking was observed during the second charging condition. Furthermore, hydrogen cracks formed during long-charging time are extended deeper within aluminum alloy specimens than those formed during high current charging condition. The aluminum hydride formed during cathodic charging was found to contribute to hydrogen embrittlement of aluminum alloy. Microhardness measurements revealed that the introduction of hydrogen caused hardening on the surface of aluminum alloy. The severity of hardening increased with either cathodic current density or charging time. Further charging increased the depth of the hardened region of aluminum alloy. Natural ageing after charging resulted in either complete or partial recovery of hardness, ultimate tensile strength and yield strength depending on the prior hydrogen charging conditions. However, the tensile ductility of hydrogen-charged aluminum alloy was not recovered to its original value (i.e. before charging) even after prolonged natural ageing.

Keywords: Cathodic hydrogen charging; AlMg1SiCu aluminum alloy; Mechanical properties; Microhardness

1. Introduction

The degradation of metals and alloys by hydrogen has been studied by numerous investigators. Watson et al. [1] studied the effect of cathodic hydrogen charging on the mechanical properties of pure aluminum and they found that the cathodic charging reduced the ductility and increased the yield and tensile stresses of pure aluminum. It was noted [2] that the ultimate tensile stress of the charged Al–4Zn–1Mg aluminum alloy was a non-linear function of the charging cathodic current density. Hydrogen was found [3] to enhance dislocation mobility resulting in crack growth in high purity aluminum. The hydrogen-assisted cracking has been observed to be close to grain boundaries in nickel [4], iron [5] and Al–Zn–Mg alloys [6]. It was concluded [7] that environmentally assisted cracking involves adsorption of hydrogen which facilitates the nucleation of dislocations at crack tips. Hydrogen embrittlement was observed in high purity iron by Kimura and Kimura [8] and they found that embrittlement is observed regardless of hydrogen-induced hardening or softening.

The effect of hydrogen on the hardness of metallic materials has also been reported by several investigators. Iost and Vogt [9] studied the hydrogen-enriched surface of an austenitic stainless steel using microhardness tests. They found that cathodic hydrogen charging changes the Vickers hardness number (VHN) of the material. The variations of VHN were related to the hydrogen content of the γ-lattice. It was concluded [9] that the increase in VHN by cathodic hydrogen charging of the material was associated with an increase in compressive stresses resulting from the diffusion of hydrogen into the γ-lattice.

It was also found [2] that cathodic hydrogen charging of Al–4Zn–1Mg alloy produced major surface hardening which

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has been explained in terms of the dislocation pinning mechanism.

Pantelakis et al. [10] observed noticeable decrease of yield, ultimate tensile stress and dramatic volumetric embrittlement in aircraft structure aluminum alloys 2024 after corrosion exposure. The observed material degradation behavior was attributed to hydrogen penetration and absorption in the alloy.

Chen et al. [11] investigated the effects of hydrogen on mechanical properties and fracture mechanism of 8090 Al–Li alloy and they noted that the tensile strengths (UTS and YS) of hydrogen-charged Al–Li alloy decrease linearly and the plasticities (RA and El) drop greatly with the decrease of strain rate. The same authors observed that the charged hydrogen enhances intergranular cracking on fracture surface of the alloy. It has been reported that the loss in ductility of Al–6Zn–3Mg is a result of intergranular hydrogen embrittlement [12].

Petroyiannis et al. [13] observed a hydrogen-rich embrittled zone just below the corrosion layer. Their fractographic analyses revealed an intergranular fracture at the specimen surface followed by a zone of quasi-cleavage fracture and further below an entirely ductile fracture in the 2024 aluminum alloy.

Kamoutsi et al. [14] investigated corrosion-induced hydrogen embrittlement in aluminum alloy 2024 and they also observed a hydrogen-rich affected zone just below the corrosion layer. The same authors found that the trapped hydrogen could be released by heat treatment which resulted in complete restoration of ductility of the alloy.

The objective of this work was to determine the effect of cathodic hydrogen charging on the mechanical properties of AlMg1SiCu aluminum alloy. Also a considerable amount of work was undertaken to determine the penetration depth of cathodically charged hydrogen into the aluminum alloy specimens by microscopic observations of cross-sections of the specimens and microhardness measurements conducting at the charged, near-charged and interior surfaces.

2. Experimental procedure

The material used in this investigation was commercial AlMg1SiCu aluminum alloy in the form of sheet. The material was supplied from the Jordan Modern Aluminum Industries Company. The chemical composition of this material was measured using energy dispersive X-ray (EDX) microanalysis system and listed in Table 1. For tensile experiments, a number of specimens were cut from the sheet with dimensions of 15 cm length, 1 cm width and 0.3 cm thickness and machined according to ASTM E8 method for tension testing. For the microhardness tests the specimens with dimensions of 3 cm length, 1 and 0.3 cm thickness were cut from the sheet. All the specimens were solution heat treated at 530 °C then artificially aged at 180 °C for 8 h.

The specimen surfaces were slightly polished using 600-grit paper in order to remove any oxide or hydroxide layer presented on the surface, which could act as a barrier to hydrogen uptake.

The cathodic hydrogen charging technique developed in the laboratory used graphite anodes. The specimen was made the cathode in an electrolytic cell. The electrolytic solution contained 75% (volume) methanol, 22.4% (volume) distilled water, 2.6% (volume) sulphuric acid and 10 mg l^{-1} arsenic trioxide to inhibit hydrogen recombination at the surface. Constant cathodic current densities between 5 and 85 mA cm^{-2} for a constant charging time of 5 h were applied to the specimens. The hydrogen charging time varied from 5 up to 72 h at a constant current density of 5 mA cm^{-2}. The experiments were performed at room temperature. All tests were carried out immediately after cathodic hydrogen charging.

The tensile tests were carried out at a strain rate of $2.4 \times 10^{-4}\,S^{-1}$, at room temperature, in air. The load–elongation curves (stress–strain curves) were recorded on a strip chart, from which strength and ductility data were calculated. Ductilities of specimens were evaluated by the total elongation, i.e. the total strain to fracture.

The microhardness was measured immediately after cathodic hydrogen charging and after various time intervals. Microhardness measurements were made on the surface as well as across the thickness of the specimens. Indentation measurements were carried out with a Vickers indenter a 25 g load for 20 s. Each measurement was the average of three indentations.

The X-ray diffraction measurements of hydrogen charged specimen were carried out immediately after removal from the charging bath using Cu Kα radiation at 40 kV and 20 mA. The external and fracture surfaces of uncharged and hydrogen charged specimens were examined by scanning electron microscope (SEM).

Table 1
The chemical composition of 1SiCu aluminum alloy used in this study

Element	Mg	Si	Cu	Mn	Cr	Fe	Al
wt.%	1.0	0.6	0.16	0.15	0.05	0.18	rem

3. Results and discussion

3.1. Tensile properties

Engineering stress–strain curves of uncharged and hydrogen-charged aluminum alloy specimens at two charging cathodic current densities for a constant charging time are compared in Fig. 1. The results indicate that cathodic hydrogen charging decreased the ultimate tensile strength (UTS), yield strength (YS) and ductility of the aluminum alloy specimens. The ultimate tensile strength was decreased by hydrogen from 290.7 to 279.5 MPa for the specimen cathodically charged at 15 mA cm^{-2} and to 258.7 MPa for another specimen charged at 85 mA cm^{-2}. The experimental results also showed that the yield strength (YS) of aluminum alloy specimens was decreased by cathodic hydrogen charging from 250.1 to 243 MPa for the specimen cathodically charged at 15 mA cm^{-2} and to 224.5 MPa for another specimen charged at 85 mA cm^{-2} as can be obtained from the linear parts of engineering stress–strain curves of Fig. 1. The percent elongation at fracture (PE) was decreased by hydrogen from 15.4% to 13.2% for cathodically charged specimen at 15 mA cm^{-2} and to 9.3% for charged specimen at 85 mA cm^{-2}.

The effect of charging time at a constant current density was also investigated. Fig. 2 shows engineering stress–strain curves of uncharged and hydrogen-charged aluminum alloy specimens for two different times at a constant current density. The results also indicate that this cathodic charging condition decreased the ultimate tensile strength, yield strength and ductility of the aluminum alloy specimens. The ultimate tensile strength was decreased by hydrogen from 290.7 to 272.4 MPa for the specimen cathodically charged for 12 h and to 235.4 MPa for another specimen charged for 72 h. The yield strength of aluminum alloy specimens was also decreased by cathodic hydrogen charging from 250.1 to 237.2 MPa for the specimen cathodically charged for 12 h and to 213.8 MPa for another specimen charged for 72 h as can be obtained from the linear parts of engineering stress–strain curves of Fig. 2. The percent elongation at fracture