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Hydrogen Induced Residual Stresses and Elastic Lattice Strain in Pure Aluminum

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Abstract

Hydrogen was introduced into pure aluminum by cathodic charging technique. The aluminum specimens were charged at different current densities of 5, 25, 50 and 100mA.cm^{-2} for a constant charging time of 10hrs. X-ray diffraction technique was used for measuring the lattice strain and residual stresses. These measurements revealed that hydrogen caused induced residual stresses and elastic lattice strain in pure aluminum. Moreover, the residual stresses and elastic strains were found to increase with either current density or charging time. The more-severe lattice distortion resulted from long cathodic charging condition.

Keywords: Residual Stresses, Pure Aluminum, CathodicHydrogen Charging.

1. Introduction

The effect of hydrogen on the material behaviors has been investigated by a numerous researchers. Hydrogen can result in an intergranular cracking in an aluminum alloy which is due to hydrogen embrittlement observed in the tensile specimens charged with hydrogen [1]. Two mechanisms were proposed to the hydrogen embrittlement which are grain boundary triple junction cracking and slip-localization-induced intergranular cracking along microvoids formed on grain boundaries [2]. The degradation of the 2024 aluminum alloy was attributed to the several consecutive stress states resulted from thermal and environmental cycling in chloride media which lead to hydrogen diffusion, transport and trapping [3]. It was found that the tensile strength was insignificantlyinfluenced by hydrogen charging of 310S stainlesssteel, while the elongation of the same material was decreased due to a ductile to brittle fracture transition [4]. It well recognized that hydrogen can enter the metallic materials in various ways such as corrosion, melting, casting, electroplating and fabrication. Hydrogen embrittlement is resulted from the hydrogen introduction into the materials by corrosion and with significant residual stress it becomes a critical problem in twinning-induced plasticity steels [5]. Hydrogen-induced delayed fracture was observed to occur in steel after deformation and the subsequent hydrogen uptake with significant residual stress [6]. The stress corrosion cracking in Mg–Al alloys is found to be associated with hydrogen which is due the thresh stress reached to about 0.5 yield strength in the elastic region of applied stress [7].

The elastic properties of iron are changed as a result of hydrogen accumulation on high density phases of the material [8]. The residual stresses resulted from the incorporation of hydrogen atoms into the zinc matrix were calculated by analyzing the obtained X-ray diffraction patterns of the hydrogenated material [9]. In the previous investigation it was found that the cathodically charged zinc exhibited brittle transgranular fracture at the surface layers and ductile intergranular fracture at the deeper layers of the material.Hydrogen-induced cracking was observed to start at the stress-concentrated intersections between primary and secondary mechanical twins, and propagatedalong the twin boundaries in Fe–18Mn–1.2C austenitic steel [10,11].

The objective of the present investigation was to measure the residual stress and elastic strain in the pure aluminum lattice induced by cathodic hydrogen charging. The effect of current density and charging time on the stress and strain behavior was also investigated in this paper.

2. Experimental procedure

The material used in this investigation was pure aluminum (99.999%) sheet with 2mm thickness and 10mm width. The electrochemical cell used for cathodic hydrogen charging consists of graphite anode, cathode and electrolytic solution. The specimen was made cathode in the cell. The electrolytic solution contains 75% (volume) methanol, 22.4% (volume) distilled water, 2.6% (volume) sulphuric acid and 10mg per litter arsenic trioxide to inhibit hydrogen recombination at the surface.

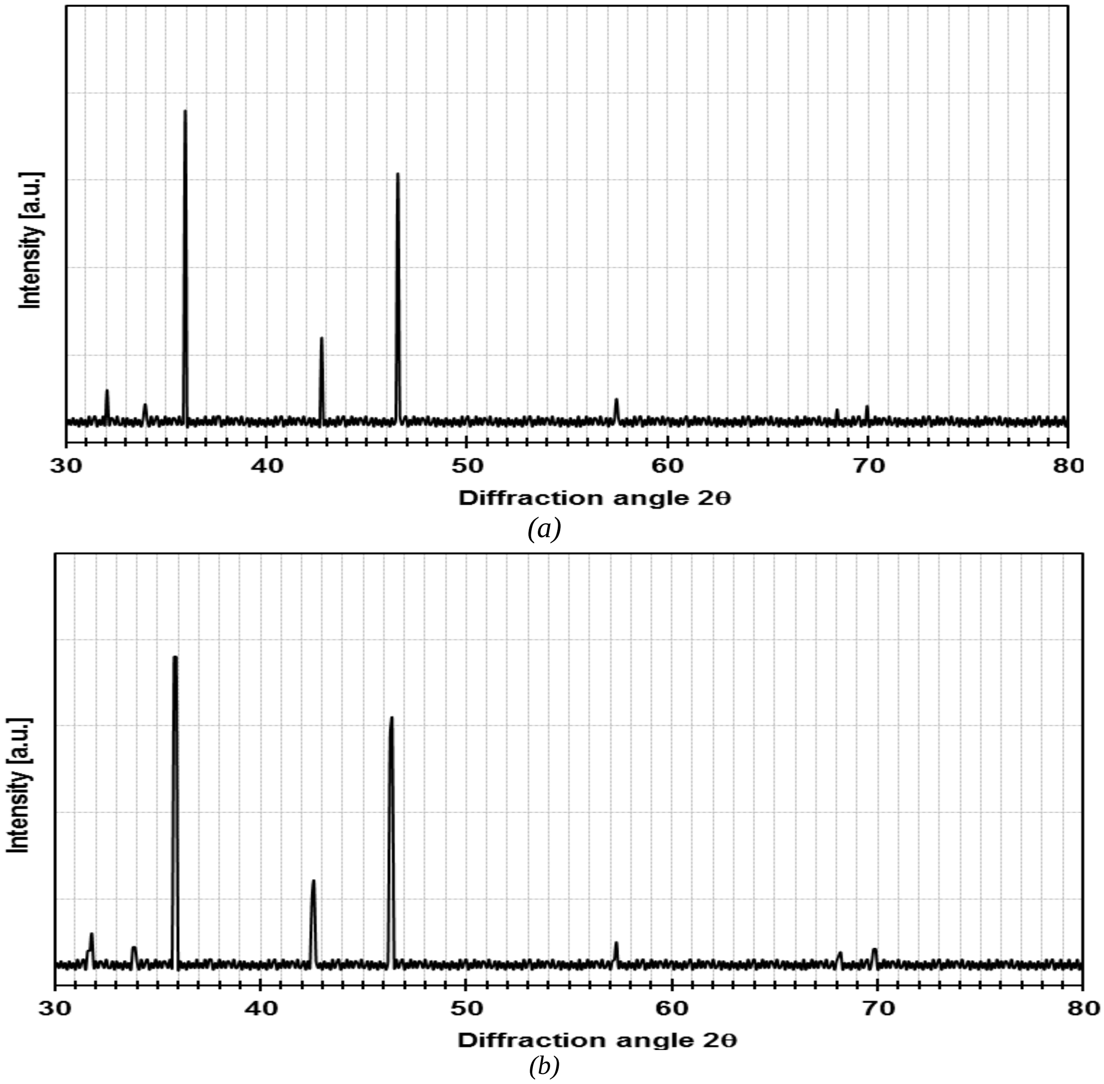
The specimens were hydrogen charged at various current densities of 5, 25, 50 and 100mA.cm^{-2} for a constant time of 3 hrs in the first series of experiments and for different charging times of 6, 24, 48 and 96 hrs at a constant current density of 2mA.cm^{-2} in the second series of experiments. The experiments were performed at a temperature of 25^{o}C.

The tensile tests were carried out at a strain rate of 2.4 x1 0^{-4} S^{-1}, at a temperature of 25^{o}C, in air. The load-elongation curves (stress-strain curves) were recorded on a strip chart. The microhardness was measured immediately after cathodic hydrogen charging. Indentation measurements were carried out with a Vickers indenter a 25gr load for 20 seconds. Each measurement was the average of three indentations.

The residual stresses were measured using X-ray diffraction technique by measuring the surface strain, which is indicated by the position of a diffraction peak for crystal planes, oriented at various angles to the surfaces of a specimen. From the stress-strain curve of pure aluminum, the stresses data corresponding to calculated strains were obtained.

3. Results and discussion

The X-ray diffraction patterns taken from the uncharged and hydrogen specimens at various current densities and those charged for different times are shown in Fig 1.



(a)

(b)

Figure 1: XRD of uncharged (a) and hydrogen charged at (b) 100 mA.cm^{-2}.

The XRD results revealed that hydrogen caused peak shift of reflections to lower 2θ values in aluminum lattice. This shifting of the peaks indicates an increase in the lattice parameters during charging. Furthermore, the peak shift increased with either current density or charging time which can be attributed to the higher trapped hydrogen resulted from the severe cathodic charging conditions applied to aluminum specimens. The XRD peak shift to lower 2θ values indicate that the tensile stresses are introduced from the cathodic hydrogen charging. These tensile stresses are increased with increasing either current density or charging time applied to the aluminum specimens.

The measurements of lattice strains revealed that the introduction of hydrogen into aluminum lattice resulted in its straining. Moreover, the strain increased with increasing the current density or charging time. The effect of the current density and charging time on lattice strain is shown in Figs 2 and 3 respectively. As can be seen, the introduction of hydrogen by cathodic charging condition of longer charging time resulted in higher lattice strain than that of higher current density for a short charging time. It is believed that the long charging time caused more hydrogen atoms to diffuse throughout the specimen and thus resulting in more lattice strain. Moreover, there was not sufficient time for hydrogen diffusion during the cathodic charging of the pure aluminum at higher current density. The strains induced by the cathodic hydrogen charging were not exceeded the plastic strain limit and therefore, they were considered to elastic strains. These strains are believed to increase the crystal imperfections such as cracks, dislocations etc.

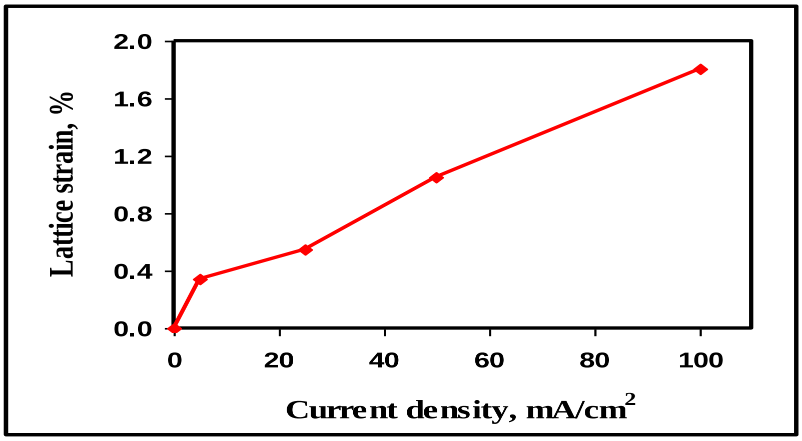


Figure 2: Effect of current density for a constant charging time on the lattice strain of pure aluminum.

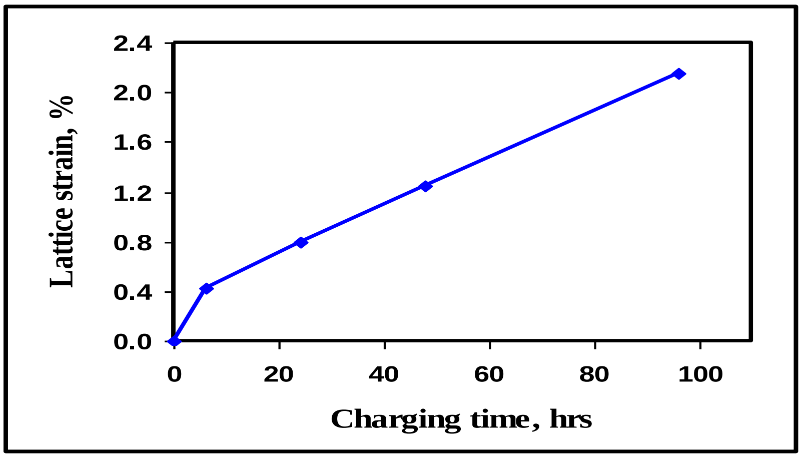


Figure 3: Effect of charging time for a constant current density on the lattice strain of pure aluminum.

It is well known the elastic distortion of the crystal lattice by interstitial hydrogen is an important quantity to measure, because it is a measure of the strength of the elastic interaction between hydrogen and internal stress fields, e.g. dislocation and crack tips, and thus may play an important role in understanding the hydrogen embrittlement of metals. It is believed that the high hydrogen pressure to be responsible for the lattice strain and the resulting reduced ductility. Hydrogen in interstitial solid solution in the metallic material produces a hydrostatic lattice distortion, and at large and inhomogeneous concentrations the lattice strains can exceed the elastic limit. Thus, even with no externally applied load new dislocations can be generated. The generated dislocations act as obstacles to atomic slipping which decrease the ductility of the aluminum on one hand and result in embrittling the material on other hand. This may explain why the hydrogen results in the hardening of the metallic materials.

The residual stresses induced by hydrogen were also found to be unique function of either current density or charging time. Figs 4 and 5 compares the approximated stresses of aluminum specimens charged at various current densities for a constant time and other charged for different times at a constant current density respectively which revealed that the residual stresses are also increased with increasing the current density. It is may be again noted that long-time of charging resulted in more hydrogen to diffuse throughout the specimens producing more severe residual stresses. These stresses are tensile as explained above and their magnitude depends on the concentrations of the absorbed hydrogen into the aluminum specimens. It is believed that the higher current density results in higher hydrogen concentrations. However, the hydrogen content are more concentrated at the surfaces of the aluminum specimens while the bulk of the specimens have less hydrogen content during this cathodic hydrogen condition. Cathodic hydrogen charging for long times at a constant current density results in the diffusion of hydrogen into the bulk of the aluminum specimens which causes more distortion in the aluminum lattice and hence higher residual stresses. This may explain why the magnitude of the residual stresses was higher in the aluminum specimens cathodically charged for longer times.

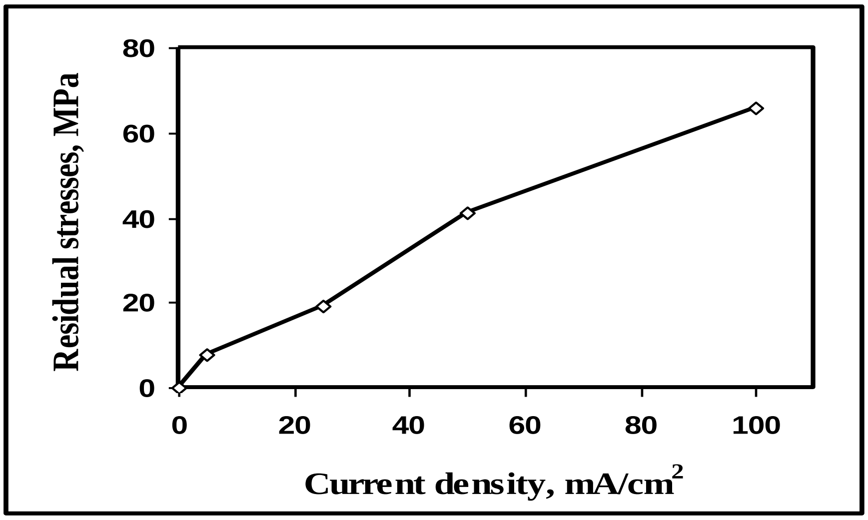


Figure 4: Residual stresses as a function of current density for a constant charging time.

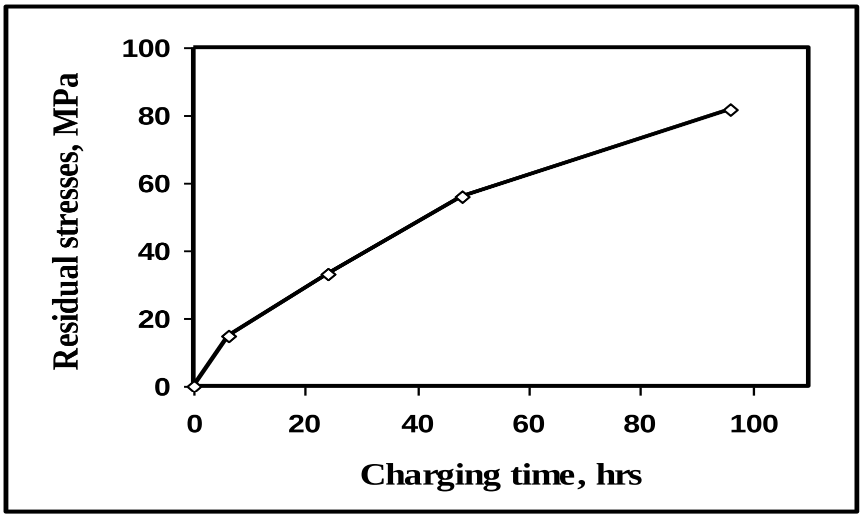


Figure 5: Residual stresses as a function of charging time for a constant current density.

To further evaluate the effects of hydrogen, microhardness measurements were conducted on the aluminum specimens before and after cathodic charging. Figures 6 and 7 showed the effects of current density and charging time on Vickers microhardness respectively. The results of these measurements showed that hydrogen induced surface hardening in the investigated material which is believed to be associated with an increase in the residual stresses resulting from the diffusion of hydrogen intoaluminum lattice. The more severe hardening was noted on the surface of the specimens charged for longer times. The effect of charged hydrogen on the microhardness can be explained in terms of the dislocation pinning mechanism. Surface hardening must be attributed to solute hydrogen and dislocation pinning at the surface region. Solute hydrogen atoms act as dislocation pinning sites contributing to the work hardening of the alloy. It is believed that higher charging current density leads to higher hydrogen fugacity while higher charging time leads to higher solute hydrogen concentration, both leading to more effective pinning of the dislocations and, therefore, decreased dislocation mobility which resulted in the hardening of the material.

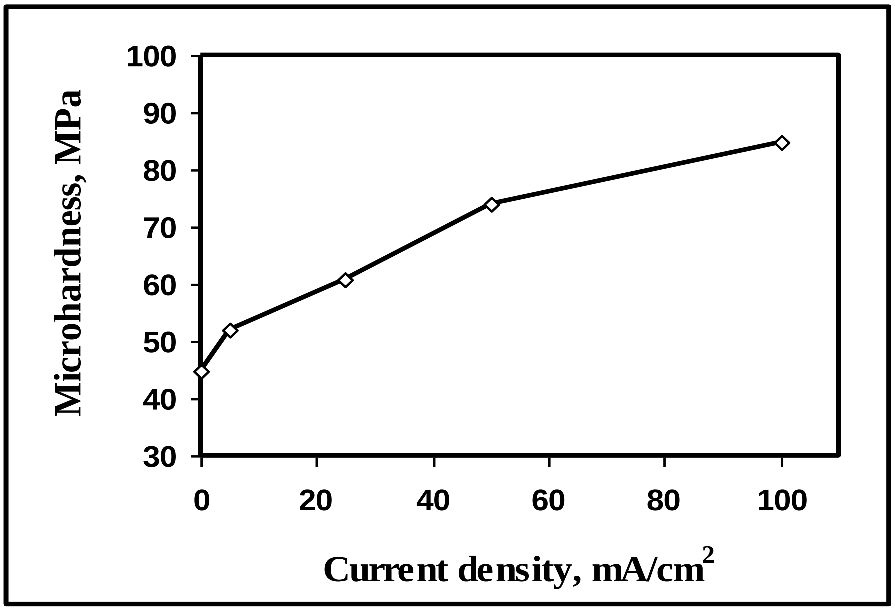


Figure 6: Effect of current density on Vickers surface microhardness of pure aluminum

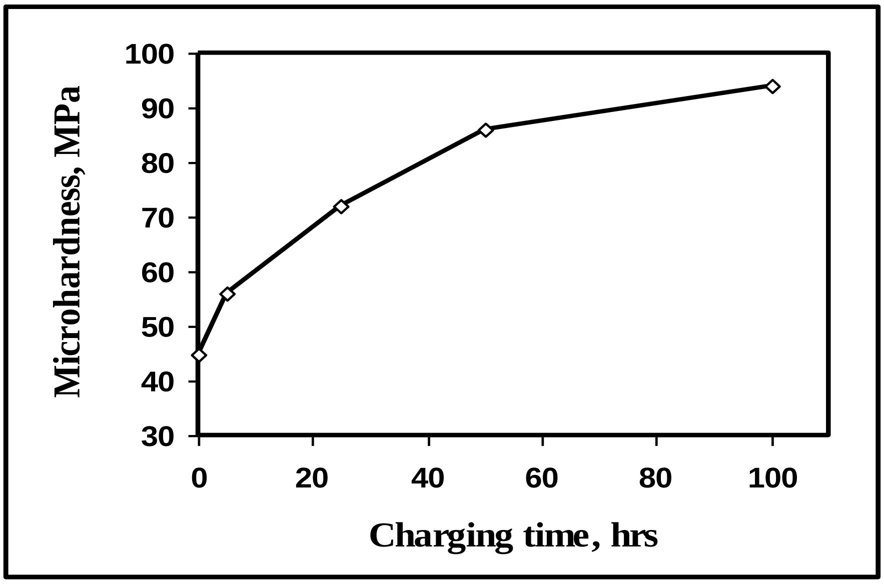


Figure 7: Effect of charging time on Vickers surface microhardness of pure aluminum

Conclusion

1. Cathodic hydrogen charging of pure aluminum induced lattice strain and residual stresses.
2. The magnitudes of lattice strains and residual stresses are depended on the cathodic charging condition applied to the material.
3. Hydrogen was also found to induce hardening in pure aluminum. The severity of hardening depended on the cathodic charging condition applied to the investigated material.

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