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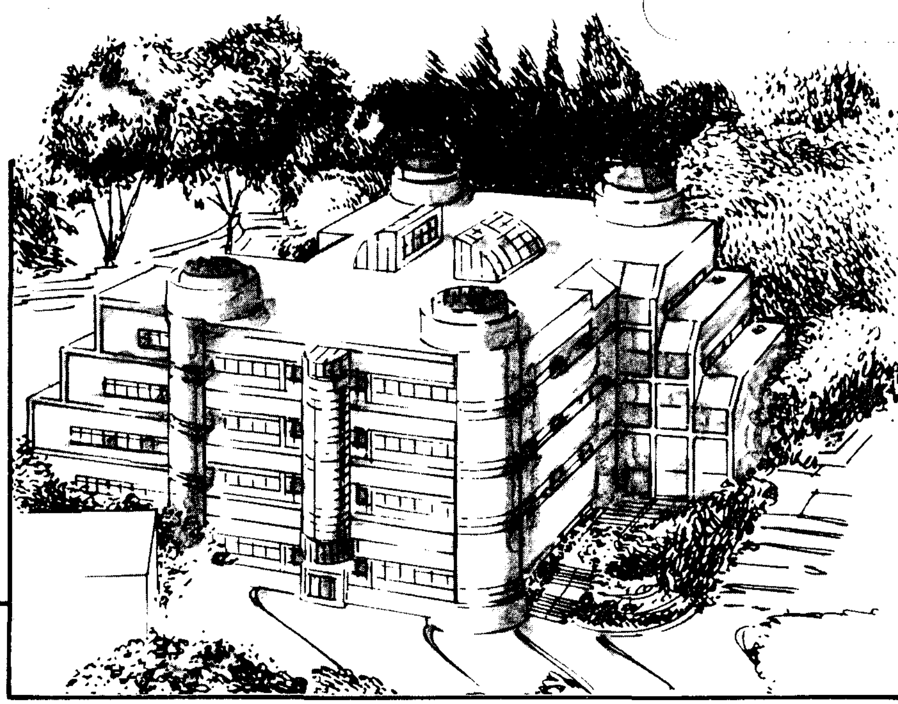

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The Effect of Hydrogen Charging on the Mechanical Properties of Aluminum Alloy 2090

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The effect of hydrogen charging on the mechanical properties of a peak-aged 2090 Al-Cu-Li sheet material was studied. Flat tensile and notched tensile specimens of longitudinal orientation were tested at 77 and 300 K in both the hydrogen charged and uncharged conditions. The results suggest a hydrogen effect appearing as a loss in the ability of the material to withstand stress triaxiality. Macroscopic analysis of the fracture surfaces reveal a greater amount of shear type fracture morphology in charged specimens which may be interpreted as a decrease in the material's ability to resist planar slip. Though differences in the microscopic fracture morphology are found between specimens tested at different temperatures and orientations, no observable difference is found between those that are charged and uncharged. Results establish that the effects of hydrogen charging on the material tested do not appear to be of significant engineering importance.

Introduction

In recent years, the aluminum alloy 2090 has received much interest due to its mechanical behavior at cryogenic temperatures. Initial investigations have proved 2090 to be a low density alloy with good weldability and corrosion resistance, and relatively high stiffness and strength. In addition, the increase in both strength and toughness with decreasing temperature for 2090, a phenomenon seen in many aluminum alloys, is the most dramatic known to date. For these reasons, 2090 is one of the alloys proposed as the primary structural material to be used for large fuel tanks in a number of aerospace systems. Such systems include the space shuttle, the National Aerospace Plane (NASP), and the Advanced Launch System (ALS).

With respect to cryogenic studies, the majority of the work done on aluminum-lithium alloys so far has been aimed toward the understanding of the parameters which control cryogenic properties. There is little work being performed on what effects a hydrogen environment may have on the mechanical properties of 2090 at cryogenic temperatures. The effects which hydrogen may produce are at best, a secondary issue since they are only a concern if the tanks are reused. Otherwise, the fuel tank will be at very low temperatures throughout its service life and the diffusion of hydrogen into the material is negligible. However, if the cryogenic fuel tanks are reused, extended exposure to residual hydrogen becomes an issue. Although the tankage system is at cryogenic temperatures during the liftoff and orbit stage, the fuel tank may experience hydrogen attack during reentry when both high temperatures and residual hydrogen gas exist. This combination may allow hydrogen gas to diffuse readily into the wall of the tank. Upon refueling and the return to cryogenic temperatures, any hydrogen present within the matrix may be trapped.

This study examines the effects of hydrogen charging on the mechanical properties of the aluminum-lithium alloy 2090-T8 at 77 K and 300 K. The purpose of this study is to ascertain if this effect is of *engineering* importance. In doing so, a brief literature review of the two most predominating theories will also be presented on the topic of hydrogen and its effects in order to provide some insight on possible mechanisms for the observed behavior.

Experimental Procedure

Originally, only one type of test was to be performed in this study, simple tension. However, results from this test indicated an effect which it was believed a notched tensile test would better reveal. Although the specimens differ in their configuration, the procedure used to prepare the specimens were similar and are described below.

Specimen blanks were cut from a 2090 sheet material (Al - 2.9Cu - 2.0Li - 0.1Zr weight percent) with a nominal thickness of 4.1 mm (0.160 in) in the T3 condition, solution heat treated and stretched 4.6%, as supplied by the Alcoa Technical Center. A final condition of T8 was achieved by peak ageing at 163°C for 32 hours followed by a room temperature water quench. All specimens, flat tensile and flat notched tensile specimens were machined in parallel to the rolling direction. Final dimensions for the flat tensile specimens were approximately 3.6 mm (0.140 in) in thickness and 3.2 mm (0.125 in) in width, with a 25.4 mm (1 in) gage length. Those for notched tensile specimens were approximately 2.5 mm (0.100 in) in thickness and 4.8 mm (0.190 in) in width, with a 31.8 mm (1.25 in) gage length. Two 60° notches of 0.8 mm (0.033 in) depth were machined into each side of the width of the specimens with the notch running in the short transverse direction.

All specimens were cleaned in a 5% sodium hydroxide solution for 5 minutes, rinsed with distilled water, then dipped in nitric acid for 10 seconds, rinsed again with distilled water and dried. This procedure eliminated inconsistencies of surface effects on hydrogen transport between test specimens by removing the already present oxide layer and allowing each specimen to form a new oxide layer in the same environment.[1]

Hydrogen charging has been used previously to study hydrogen effects in a number of aluminum alloys, the best documented of which is 7075, commonly used in commercial aircraft.[2-6] The charging procedures used in this study resemble those used for these earlier studies. Specimens to be tested for hydrogen effects were cathodically charged in a hydrochloric acid solution of pH = 1 for a minimum of 16 hours under an applied constant potential of -1500 mV versus the standard calomel electrode.[3-5] For 7075, hydrogen effects do not vary with charging times between 5 and 24 hours.[4] It was assumed that the properties of 2090 were similar in this respect. More recent work has also shown that for 2090, the amount of adsorbed hydrogen approaches a maximum asymptotically with the charging time.[7] Cathodic polarization curves were generated to verify the formation of hydrogen.

Charged and uncharged specimens were tested at temperatures of 77 K and 300 K. Charged specimens were tested within five minutes after completion of charging to reduce the possibility of hydrogen outgassing. All mechanical tests were performed in a servohydrualic testing machine equipped for cryogenic testing. Two tensile tests were performed per condition at a strain rate of 6×10^{-4} s^{-1}. Previous work by Taheri, et. al. was used as a guideline in choosing the strain rate. In their work, a maximum effect due to hydrogen charging was found to lie within a range of 10^{-2} to 10^{-4} s^{-1}.[5] In a more recent publication, Kim, et. al. performed tensile tests at a strain rate of 5.6×10^{-4} s^{-1} on hydrogen charged 2090[7] which is also comparable with the strain rate used in this study. Due to limited material, only one notched tensile test was performed per condition. A slower displacement rate was opted for in hopes of promoting a greater amount of hydrogen diffusion. Due to the constraints of the testing machine a displacement rate of 10^{-5} inches per second was selected. Fracture surfaces of all specimens were examined using a scanning electron microscope.

Results and Discussion

An etching of the longitudinal-short transverse plane is shown in Figure 1 along with the same plane taken from an etched surface of a 12.7 mm (0.5 in) 2090-T8E41 plate material.[8] The grains in the sheet material are comparatively shorter and less defined. Fracture surface analysis, which will be discussed later, reveals that the grains identified by differing contrasts in Figure 1 consist of subgrains. It is believed that the differences in the grain morphology observed in the sheet material of this study is a result of extensive texturing due to a greater degree of cold rolling. One of the effects of this and other differences is the absence of macroscopic delamination, a phenomenon observed and well characterized in the 12.7 mm (0.5 in) plate material. These differences are the subject of future research.

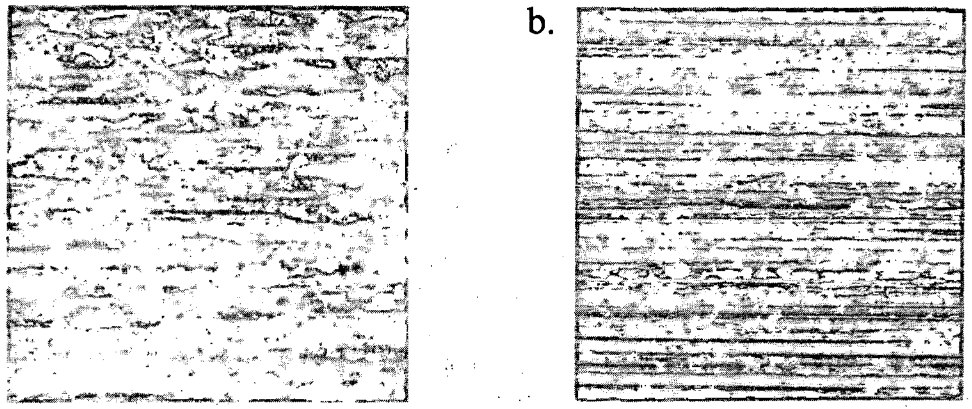

Figure 1: Optical micrographs of the etched surfaces of the longitudinal-short transverse plane of 2090-T8 sheet material (a), and 2090-T8E41 plate material (b).

Tensile properties in the uncharged and charged conditions are tabulated in Table I. Note that the strength, elongation, and area reduction increase with a decrease in temperature. A dual increase in both strength and elongation has been observed previously in this alloy in the form of a 12.7 mm (0.5 in) plate material tested at mid-thickness.[8] However, the increase found for the sheet material tested in this study was considerably less dramatic than that found for the plate material.

	Yield / Ultimate Strength (MPa)		Uniform / Total Elongation (%)		Reduction in Area (%)		Notch to Yield Ratio	
Temperature (K)	77	300	77	300	77	300	77	300
Uncharged	592 / 676	508 / 554	10.3 / 10.8	8.0 / 8.9*	11.3	10.3	0.70	0.69
Hydrogen Charged	568 / 659	506 / 552	9.6 / 9.7	7.3 / 7.4	10.1	9.4	0.76	0.72

* Values obtained from one test. All others are averages of two tests.

Table I: Measured Mechanical Properties of 2090-T8 Sheet at 77 and 300 K.

As tabulated in Table I, a relatively fixed drop in the area reduction, roughly 1 to 2 percent regardless of test temperature, is observed for the material tested after hydrogen charging. The effects observed are much smaller than in 7075, in which 20 to 40 percent drops in area reductions have been quoted in a number of articles.[3-5] 7075 however, is much more ductile than 2090 which would account for the low numbers calculated. Albrecht, et. al. have also observed a monotonic decrease in the area reduction with decreasing temperature for 7075,[3] but because of the low values calculated in this study, the consistency in the reduction of area found for 2090 may be due to the inability to resolve any trend present. The low values however, corroborate well with the results of Kim, et. al., who have observed an approximately 2 percent decrease in the fracture strain of a 12.7 mm (0.5 in) 2090-T81 plate tested at room temperature after hydrogen charging for 12 hours.[7]

Note that the ultimate and yield strength change negligibly upon charging, whereas the area reduction and elongation show a drop with hydrogen charging. This suggests that the hydrogen in the aluminum-lithium matrix is not affecting the interaction of dislocations with microstructural obstacles, but rather is isolated to the deformation and failure process after the ultimate strength is reached. This hypothesis is corroborated by the composite plots of σ and $\partial\sigma/\partial\varepsilon$ versus ε taken for the specimens as shown in Figure 2. Hydrogen charged samples exhibit a slight decrease in the amount of strain to fracture after the necking criterion is reached for both 300 and 77K. This can be seen from the longer extension of the strain hardening rate in the uncharged specimens. Note that both uncharged and hydrogen charged specimens satisfy the necking criterion. This implies that failure occurred due to geometric instability for both cases. By definition, stress triaxiality accompanies geometric instability which invalidates strain hardening rate calculations beyond the necking point. However, the ability of the material to sustain the instability can still be seen by taking the difference between the total elongation and the uniform elongation, the strain at which the ultimate strength is reached and the necking criterion is satisfied. Table II displays the differences. Combined, these two results, the composite plots and the calculated values of the additional amount of strain beyond the necking point, suggest that hydrogen charging reduces the ability of the material to sustain stress triaxiality.

Temperature (K)	77	300
Uncharged	0.5	0.9
Hydrogen Charged	0.1	0.1

Table II: Amount of strain to fracture after the necking criterion is reached.

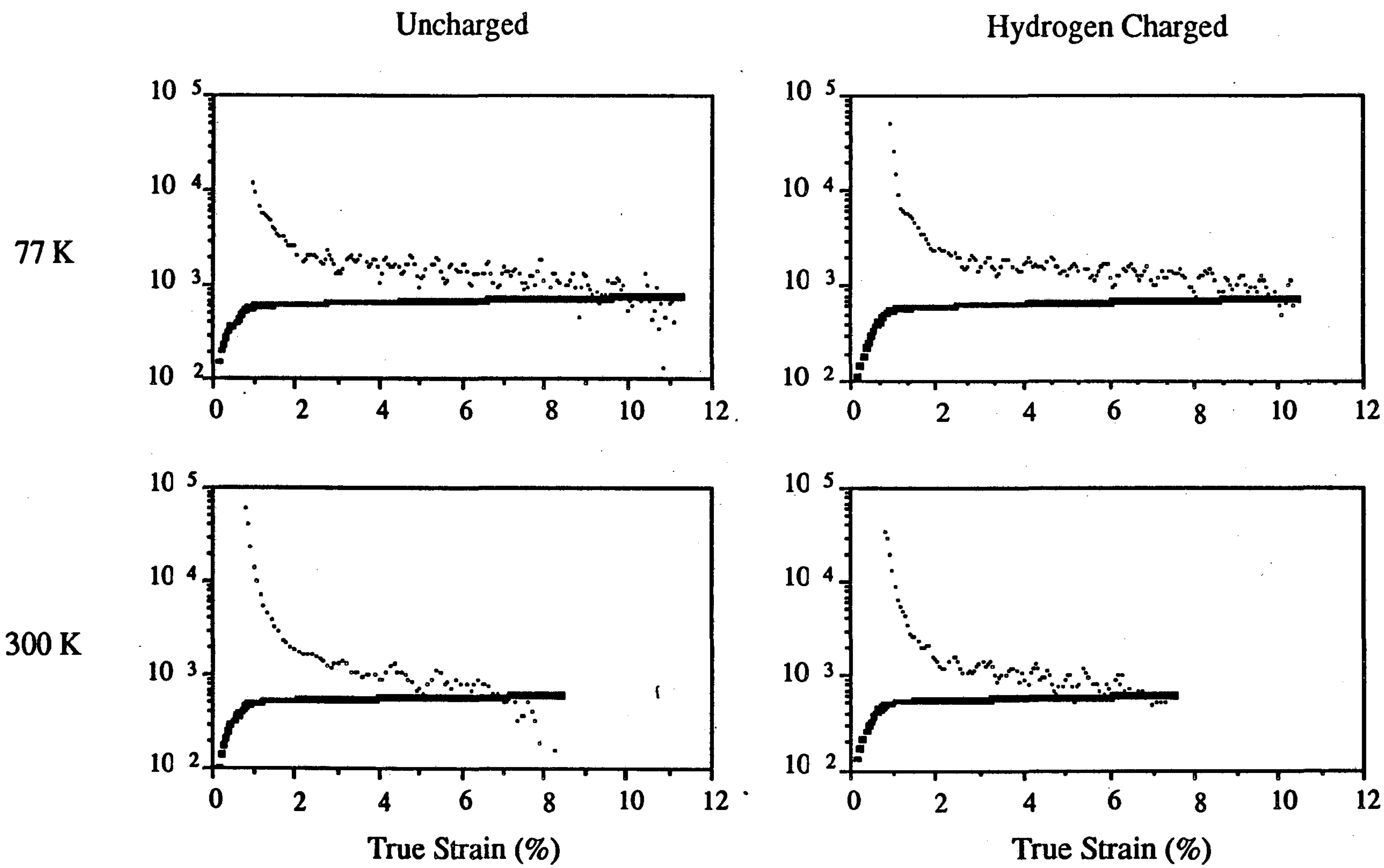

Figure 2. Composite plots showing true stress and strain hardening rate in MPa versus true strain. Note the decrease in the extension of the strain hardening rate with hydrogen charging.

Comparative analysis of the fracture surfaces of both uncharged and charged samples revealed very little. Although there are obvious differences between samples tested at 77 and 300 K, there was very little difference observed in the fracture surface between uncharged and charged samples. Though there appeared to be a larger region of macroscopic shear type fracture morphology in the charged samples, this feature could not be resolved conclusively. Micrographs of the fracture surfaces of tensile specimens for all conditions tested are shown in Figure 3. In a recent study, Kim, et al, observed a decrease in the amount of ductile tearing in a 2090 12.7 mm (0.5 in) plate material upon hydrogen charging and testing at room temperature.[7] They attribute this result to the greater promotion of delamination upon hydrogen charging. As mentioned earlier, no delamination is observed for the sheet material.

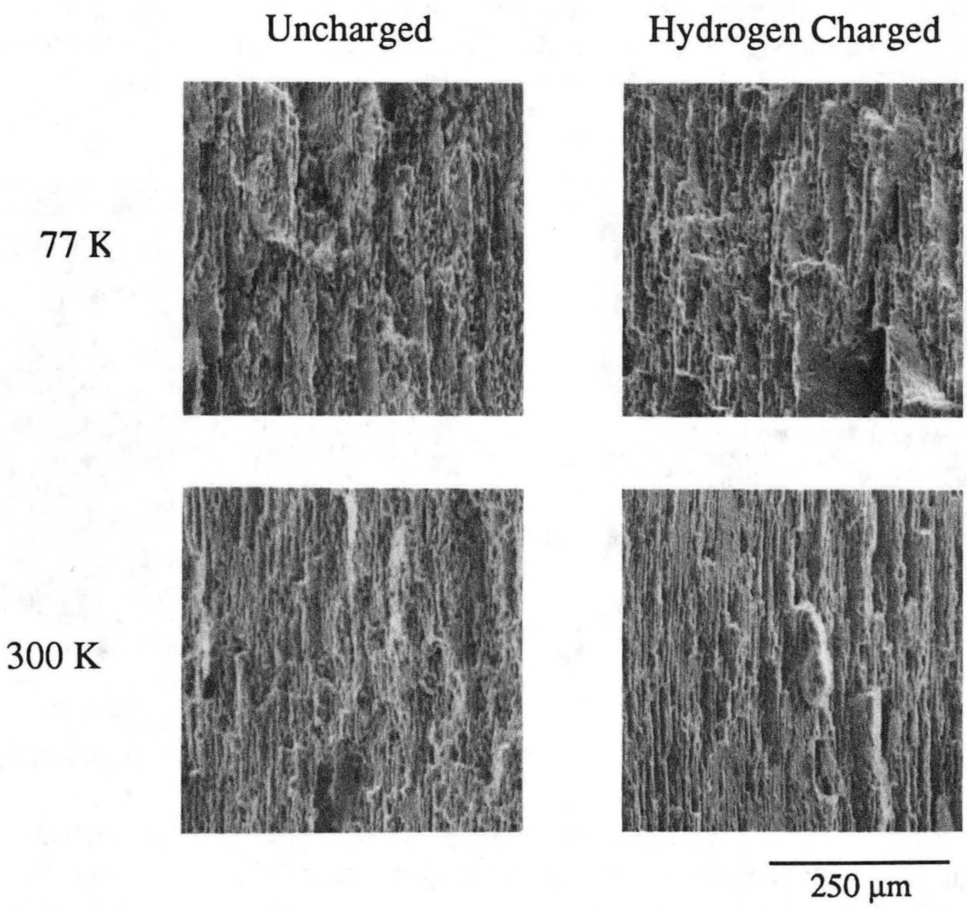

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Figure 3: Scanning Electron micrographs revealing the fracture surfaces of 2090-T8 tensile specimens.

Since the results indicate that the majority of the effects due to hydrogen charging occur during the period of stress triaxiality, additional tests were done on notched tensile specimens. The notch strength to yield strength ratio is included in Table I. In comparing the calculated values, specimen to specimen scatter must be considered since only one test was performed per condition. The numbers are fairly close in value and if taken for true, the plot indicates toughening due to hydrogen.

Notched tensile specimens have a very characteristic macroscopic fracture profile ranging from slightly oblique to fully oblique as described in ASTM Standards E338. These rankings describe the relative distribution of slant and flat type fracture morphologies. In general, a greater proportion of slant type fracture indicates a decrease in the material's ability to resist shear and/or planar slip. Hydrogen charged specimens did reveal this characteristic relative to those that were uncharged. This is illustrated in Figure 4. In general, regions of flat fracture exhibit a ductile fracture morphology with distinct dimples. Regions of slant fracture show facets which can be interpreted as transgranular shear connected by cracks along the grain boundaries. However, no significant differences were found between the individual areas between charged and uncharged specimens.

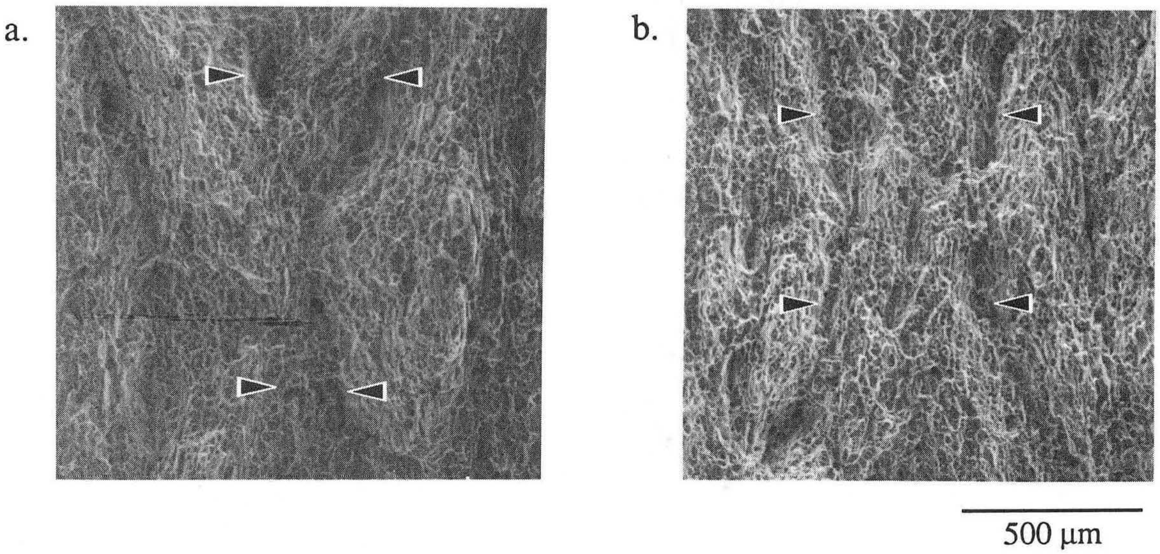

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Figure 4: Scanning electron micrographs revealing the fracture surfaces of notched tensile specimens tested at 300 K. Lines separating flat and slant regions, indicated by arrows, in charged specimens (a) are closer together than those for uncharged specimens (b). Secondary lines in Figure 4a lie between two regions of shear.

The effects of hydrogen in face-centered cubic materials have been studied extensively, specifically for nickel[9], stainless steels[9,10], and aluminum alloys[2-7,9]. In most works, a ductility loss has been the primary observation associated with the presence of hydrogen.[2-7,9] Although this study sheds no light on the validity or invalidity of either theory, it is worthwhile to briefly examine them. At present, there are two schools of beliefs as to the source of this ductility loss. Both models suggest an acceleration of ductility, one by the promotion of planar slip[11] and the other by an accelerated rate of void coalescence[12]. The latter, first suggested by Bastien and Azou, involves the transportation of hydrogen through the matrix in the form of Cottrell atmospheres on moving dislocations.[13] This mode of transport allows a rapid dislocation sweeping of hydrogen rather than the much slower mode involving lattice diffusion. A transport mechanism of this type allows hydrogen to be transported to microvoids or inclusions, which can change the rate of void nucleation and growth, thus accelerating void coalescence and ductile fracture.

Although this model may be true for other aluminum alloys, it has been suggested that the poor ductility of aluminum-lithium alloys is attributable to the formation of a stable hydride of lithium or of aluminum and lithium. It is suggested that lithium reacts with hydrogen to produce these hydrides on the slip surface, hence promoting planar slip and accelerating ductility.[11] Lithium hydride has been found in the form of subsurface particles in an aluminum-lithium binary alloy. Dickenson, et. al. propose that atomic hydrogen diffuses along the grain boundaries within the aluminum matrix and upon encountering a sufficient concentration of lithium, lithium-hydride is precipitated heterogeneously at the grain boundaries.[14] If lithium-hydride acts as a grain boundary contaminant in 2090, this would explain the increase in delamination observed by Kim, et al.[7] It is important to note that all of the work on lithium hydride to date has been on its formation during casting and there has been very little work done on its formation during exposure to a hydrogen environment.[11,14]

Conclusion

The most prominent effect due to hydrogen charging found in this study of a 2090-T8 sheet material is a decrease in the total elongation at a constant ultimate strength as revealed by tensile data and composite σ and $\partial\sigma/\partial\varepsilon$ versus ε plots. This evidence points toward a sensitivity to stress triaxiality. However, notched tensile data indicate no drop in toughness. Hence the increased sensitivity to stress triaxiality itself appears to be a very small effect. Analysis of the fracture surfaces show a greater amount of macroscopic shear type features with hydrogen charging which supports the theory of accelerated ductility upon hydrogen charging frequently quoted in the literature. However, the conclusiveness of this theory is still under debate and remains, at best questionable.

The effect of hydrogen, at first sight, does not appear to be of immense importance. The structural integrity of the material, from an engineering point of view, does not degrade significantly and thus it appears that the fuel tanks can be reused with little concern of long range effects due to hydrogen. Further analysis of the results obtained in this study may prove interesting from a scientific perspective. However, the primary goal of this work was to determine the engineering importance of the effects of hydrogen. The effect of hydrogen resides primarily in the deformation process after the ultimate strength is reached and thus can readily be avoided for most of the potential engineering applications in which this alloy will be used.

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