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M. R. Louthan, Jr. and A. H. Dexter

E. I. du Pont de Nemours and Company
Savannah River Laboratory, Aiken, S. C. 29801

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M. R. Louthan, Jr. and A. H. Dexter
E. I. du Pont de Nemours and Company
Savannah River Laboratory, Aiken, SC 29801

Intergranular fracture, with very limited plastic deformation in the grain body, accompanies blister formation in 1100 aluminum exposed to humid air in a muffle furnace at 773°K. This contrasts with the transgranular fracture by microvoid coalescence typical of hydrogen-charged aluminum, but is similar to observations[1] of intergranular cracking of high strength Al-Zn-Mg alloys exposed under stress to moist air.

Blisters are known to form on surfaces of aluminum heated in water vapor.[2] The vapor reacts with aluminum to form aluminum oxide and atomic hydrogen, which is absorbed. The aluminum lattice becomes supersaturated with hydrogen after the reaction, because the effective atomic hydrogen pressure during the reaction is many times the equilibrium pressure. Subsequent precipitation of molecular hydrogen as "voids" leads to the development of high pressures and blisters. The aluminum oxide formed during the reaction retards hydrogen evolution,[3] and thus enhances blister formation.

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Blisters were developed on 2.5 x 10^{-4}m-thick discs of 1100 aluminum annealed in room air in a muffle furnace at 773°K. After this treatment, several of the blisters were opened to establish the topography of the internal surface (Figure 1). The blistering process was clearly intergranular fracture (Figure 2).

Although a large number of the Fe_3Al precipitates were apparent on the grain surfaces, and holes corresponding to sites where precipitates were removed from adjacent grain surfaces were often found, the precipitates were neither broken nor surrounded by regions of large plastic strain. This observation is quite similar to results of stress-corrosion tests of high strength aluminum alloys, which show[1] that "the crack does not cut through grain boundary precipitates, but passes along the incoherent interface between the precipitates and one of the grains." The stress-corrosion study concluded that cracking results from grain boundary penetration by hydrogen; thus, similarities between such cracking and hydrogen-induced blistering might be expected.

Matching of adjacent grain surfaces indicated that little plastic deformation accompanied blister development, although crack-tip blunting was apparent. The surface topography of unopened blisters also indicated a lack of plastic deformation within the grains. The surface upheaval was characterized by distinct steps at grain boundaries and no apparent surface rumpling in other regions (Figure 3). Surface cracking was not noted, even adjacent to the grain boundary steps. This observation indicated grain displacement by shear along the entire length of the boundary. This type of displacement is often termed grain boundary sliding.

Grain boundary sliding and intergranular fracture during hot creep of aluminum alloys in specific regions of temperature and strain rate is well established;[4,5] the ratios of grain boundary to matrix strain are typically 0.1[4] with values as high as 0.95 being observed.[5] Relatively pure aluminum alloys, such as 1100, normally fail transgranularly at all temperatures even though grain boundary sliding may accompany deformation (i.e., the strain ratio is near 0.1). However, the tendency to grain boundary sliding is very sensitive to impurities and may be increased by absorbed hydrogen, and intergranular fracture may result.

The tensile properties of 1100 aluminum are generally unaffected by exposure to gaseous hydrogen, and the fracture mode of tensile bars is also unchanged.[6-10] Typically, final fracture of tensile bars goes through two stages at room temperature (Figure 4a). The first stage is necking of the tensile bar from a circular to a triangular cross section (the specific shape is probably texture dependent) with concurrent development of internal surfaces by microvoid coalescence; in the second stage, necking continues until fracture occurs. At more elevated temperatures, the microvoid sheet is not formed and failure occurs by necking to ∿100% (Figure 4b). Hydrogen exposure at near room temperature has no apparent qualitative or quantitative effect on either the size of the region of microvoid coalescence or the average size of the microvoids.

Typical regions of microvoid coalescence are shown in Figure 5 for both unexposed and hydrogen exposed specimens ruptured in air and in 69 MPa hydrogen at room temperature. At higher temperatures, the region of microvoid coalescence diminishes and at 773°K, fracture develops almost totally by reduction in cross section (Figure 4b). Thus, the blister topography is not typical of mechanical rupture. The differences in fracture surface topography between blistering and tensile rupture show that the absorption and subsequent precipitation of hydrogen to form a blister changes the fracture mode and thus is a form of hydrogen embrittlement. These data indicate, as has been previously proposed,[9] that aluminum is generally resistant to embrittlement by hydrogen absorption from the gas phase but that if sufficient hydrogen is absorbed embrittlement may result.

The mechanism of embrittlement during blistering clearly involves high pressures generated by precipitation of gaseous hydrogen. Because the blister is intergranular, such precipitation probably occurs at grain boundaries. However, in addition to the pressure, the large amounts of hydrogen near the grain boundaries must affect grain boundary plasticity and/or cohesion. Such effects could be similar to those of other alloying elements, which control, to a major extent, the degree of grain boundary sliding that accompanies plastic deformation.[4] However, the observed blister topography can also be explained by the hydrogen embrittlement theory,[11] which invokes reduction of the cohesive energy of the lattice by absorbed hydrogen.

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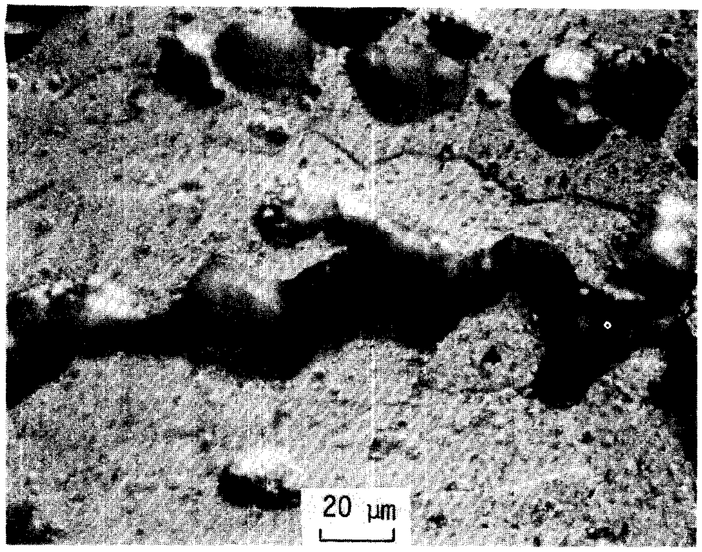
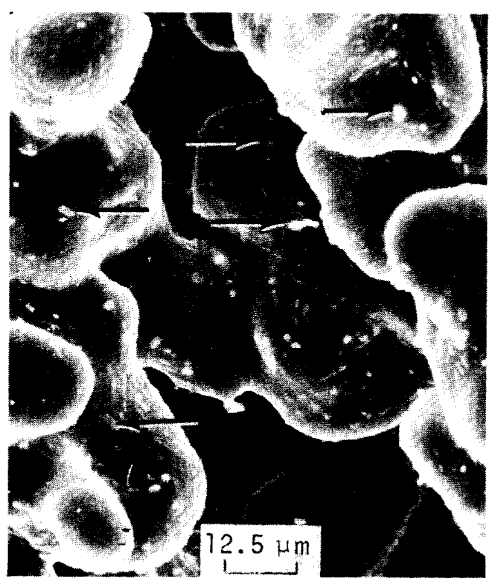
Fig. 1 Opened/Undisturbed Blisters on the Surface of 1100 Aluminum



(a) Blister Cross-Section



(b) Topography of Blister Interior
Arrows Point to Fe_3Al Precipitates.

Fig. 2 Intergranular Fracture Leading to Blister Formation

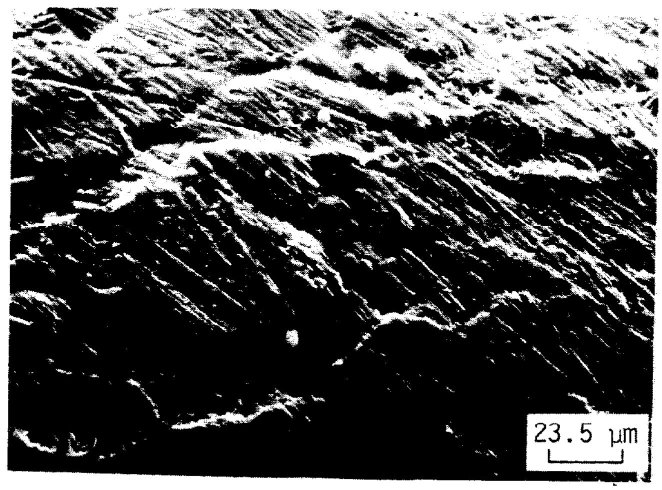
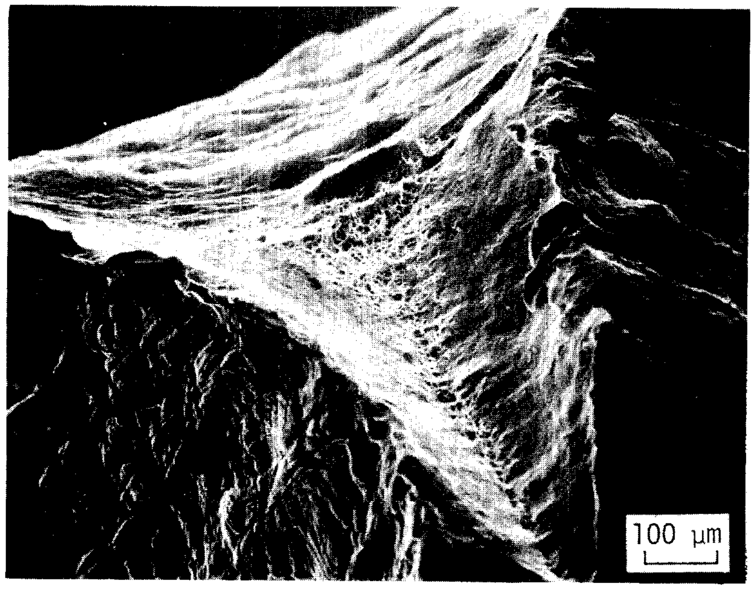
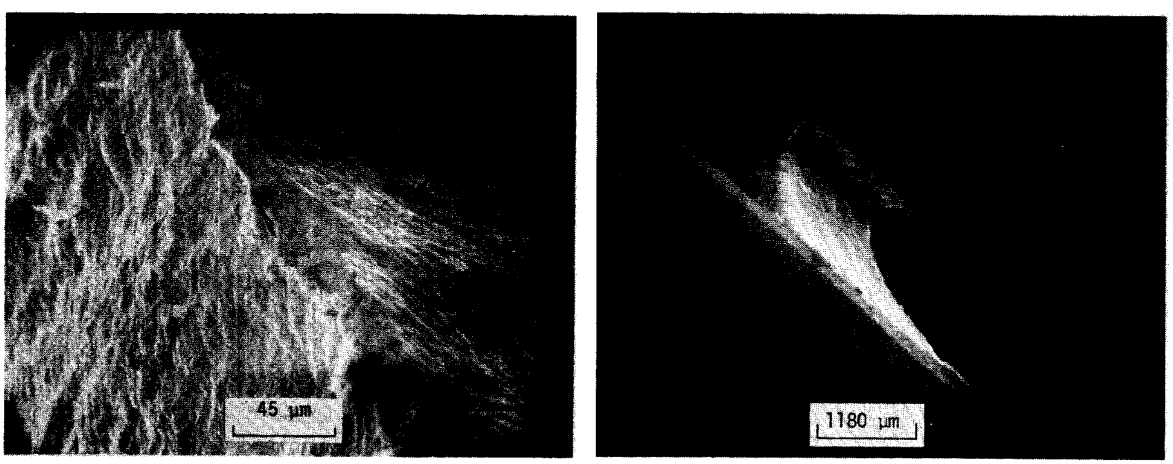


Fig. 3 Surface of Unopened Blister

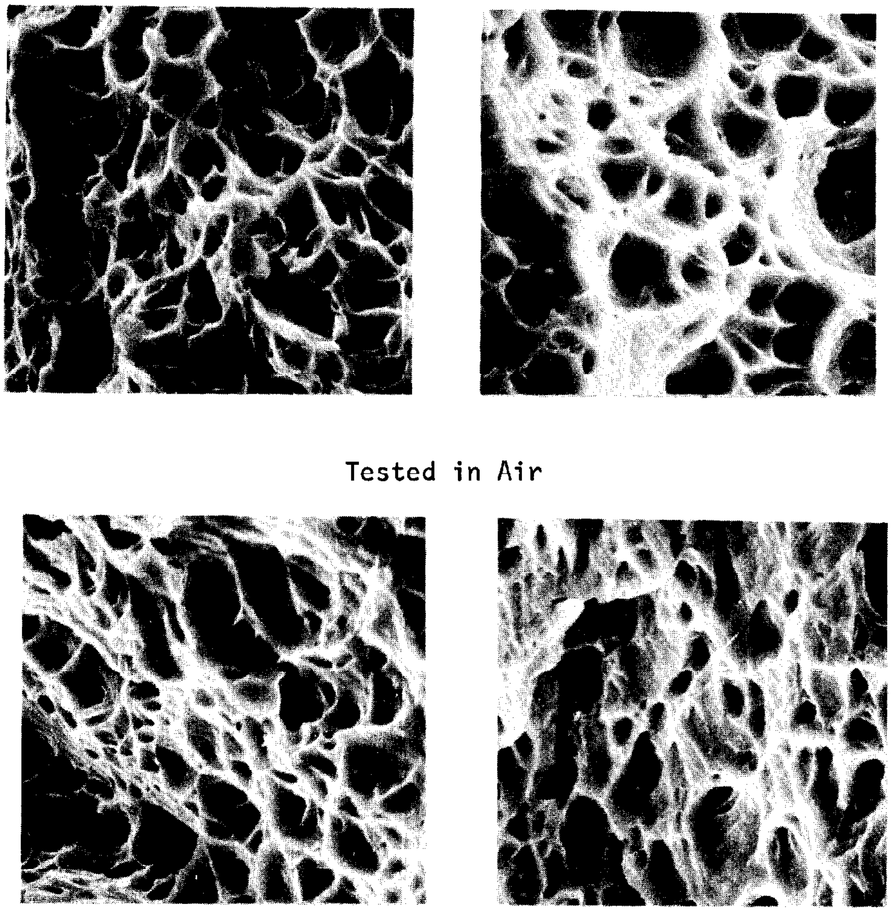


(a) Specimen Strained to Fracture at Room Temperature



(b) Plate Specimen Tested at 773°K

Fig. 4 Fracture Surfaces of Tensile Specimens



Tested in Air

Control

Charged

10 μm

Tested in 69 MPa Hydrogen

Fig. 5 Typical Topography of Region of Microvoid Coalescence in Tensile Fracture of 1100 Aluminum