


Influence of Hydrogen Embrittlement on the Localization of Plastic Strain in Al–Cu–Mg Alloy

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Abstract—The influence of hydrogen embrittlement of the aluminum Al–4%Cu–0.2%Mg alloy on the parameters of localized plastic strain is studied. Digital speckle photography is used to visualize the localized strain patterns in the D1 alloy. The velocity of localized deformation bands as a function of the yield strength for nonhydrogenated and hydrogenated samples is found.

Keywords: hydrogen embrittlement, duralumin, plastic deformation, plasticity, digital speckle images, localization
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INTRODUCTION

New methods for analyzing the inhomogeneity of plastic deformation significantly enhance the understanding of the nature of the localization of plastic deformation and the destruction of metals and alloys [1, 2]. Aluminum alloys tend to display jerky flow, which is accompanied by the periodic formation of macroscopic localized-deformation bands and their propagation along a sample. This phenomenon can be considered as the self-organization of a deformed solid [2]. Investigations of the influence of various factors on the effect of jerky flow (the Portevin–Le Chatelier effect (PLC)) have been carried out by many authors beginning from its discovery [3]. Despite the studies of the formation of deformation bands in the case of jerky flow in aluminum alloys, there are to date [1] no complete data on the inhomogeneity of the plastic deformation of aluminum alloys subjected to electrolytic hydrogenation, which significantly hinders the development of corrosion-resistant structural alloys and their processing. The aim of the work is to study the influence of the time of hydrogen saturation of aluminum Al–Cu–Mg alloys on the characteristics of localized deformation at the macroscale level.

EXPERIMENTAL

A precipitation-hardened aluminum Al–4% Cu–0.2% Mg alloy (D1) was the object of investigation. After the pressing of a hot-rolled sheet, samples were subjected to artificial aging at $T = 340^{\circ}\text{C}$ for 3 h with subsequent cooling in a furnace. The alloy was subjected to electrolytic hydrogenation at a constant cathode potential of -430 mV in 0.1 N sulfuric acid solu-

tion in a three-electrode electrochemical cell for 24–120 h [4, 5]. The samples in the shape of double blades with dimensions of $50 \times 10 \times 2$ mm in the working part were subjected to mechanical tests by uniaxial tension at a rate of $6.67 \times 10^{-5} \text{ s}^{-1}$ on a Walter + Bai AG LFM-125kN test machine. A high-resolution camera recorded speckle images of the sample surface during deformation. The images formed in the light of a semiconductor laser with a wavelength of 635 nm. The technique of optical measurements [6, 7] makes it possible to record the field of strains in a sample directly during loading by statistically analyzing speckle patterns. The kinetics of the nucleation and the propagation of localized deformation bands is analyzed using chronograms, which represent the position of the fronts of localized plastic deformation as a function of the total deformation (time).

RESULTS AND DISCUSSION

The samples of the D1 alloy to be studied were divided into three groups according to their states: (1) initial state; (2) after hydrogenation for 100 h; (3) after hydrogenation for 120 h. Figure 1 presents stress–strain curves of the samples. Table 1 lists the corresponding mechanical properties of the samples. The plasticity and the strength of the material decrease with increasing hydrogen content in a sample. According to [8], hydrogen in aluminum alloys is in a free state, thus increasing the porosity of a sample, which, in turn, reduces the strength and plasticity. An oxide film formed on the aluminum surface prevents hydrogen diffusion. Therefore, the presence of an aggressive medium significantly increases the possi-

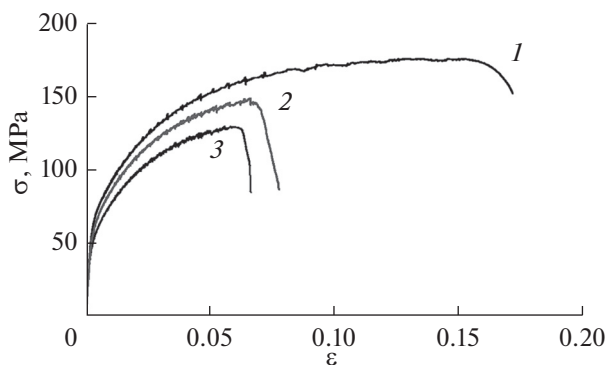


Fig. 1. Stress–strain curves of the D1 alloy in the initial state (1) and after electrolytic hydrogenation for (2) 100 h and (3) 120 h.

bility of saturation with hydrogen. Hydrogen can be stored in material for a long time, even at elevated temperatures.

Regardless of the hydrogen content, the deformation of the samples was accompanied by the appearance of a characteristic sawtooth profile on the stress–strain curve, which is a consequence of the Portevin–Le Chatelier effect [3]. For all samples, the appearance of jerky flow was accompanied by the periodic generation and propagation of localized deformation bands. The statistical processing of the speckle images provided information about the positions of localized deformation bands at any time during loading from its beginning to the sample fracture. Figure 2 shows the sequential images of the formation of a double front (two bands) of localized deformation for a nonhydrogenated sample. The horizontal axis (x) is directed along the working part of a sample. The onset of the front of localized deformation is accompanied by relaxation of stresses on the stress–strain curve. Each relaxation period corresponds to only one double front, which is an autowave of switching according to the classification of autowaves [2]. Such localized plastic deformation is typical of aluminum alloys exhibiting jerky flow [3, 9]. It should be noted that defects on the surface of the hydrogenated samples

caused by layer corrosion do not significantly affect the propagation of localized deformation bands.

The localized plastic deformation with increasing total deformation was analyzed with the help of chronograms representing a time-extended result of statistical processing of speckle images on the axial line of a sample parallel to the loading axis (Fig. 3). The horizontal axis in Fig. 3 represents the total deformation of a sample $\varepsilon \sim t$. The vertical axis is the coordinate on the working axis along which the tension occurs. Points on the chronogram indicate the position of the localized plastic deformation front along the sample axis at given moments of time t corresponding to specific values of total deformation ε . Vertical discontinuities on the chronogram result from the stopping of the propagation of one front of localized deformation and the subsequent nucleation of another double front (band) in another part of the sample. These chronograms give the information about the propagation velocity of a deformation band and can be used for constructing the dependences of the velocity on the total strain [9] or acting stresses. Note that, after 1.5% of total deformation before sample fracture, the region of propagation of localized deformation bands becomes limited near the region of subsequent fracture. An increase in the total deformation narrows this region gradually and it turns into a fracture nucleus, as can be seen from Fig. 3.

The velocity of the bands as a whole was found to decrease with increasing deformation. However, this dependence is nonlinear, whereas the dependence of the velocity of bands on the effective stresses is linear with the correlation coefficient $R = 0.98$ (Fig. 4a).

It should be noted that the slope of the lines that correspond to the rate of change is higher for hydrogenated samples. The number of jumps on the stress–strain diagram and the velocity of the bands at the beginning and at the end of the plastic flow are independent of the degree of hydrogen saturation of a sample. In this case, the process of localization of deformation is related to the length of the stages of plastic flow, which shrink after hydrogenation, and is a manifestation of the self-organization of the deformed medium in the case of hydrogen embrittlement. Figure 4b shows

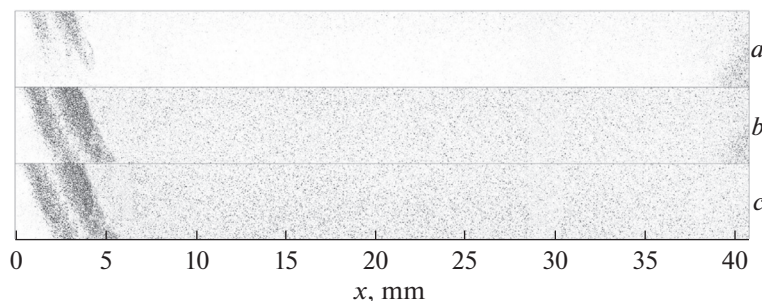


Fig. 2. Onset of the double front of localized deformation in the nonhydrogenated D1 alloy: (a–c) sequential images of the working surface of the deformed sample at a step of 0.3 s.

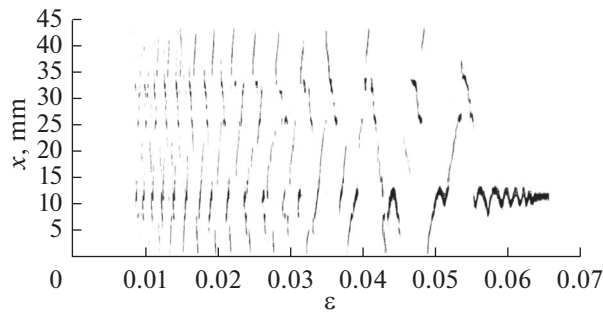


Fig. 3. Chronograms of the positions of localized deformation bands in the D1 alloy hydrogenated for 120 h.

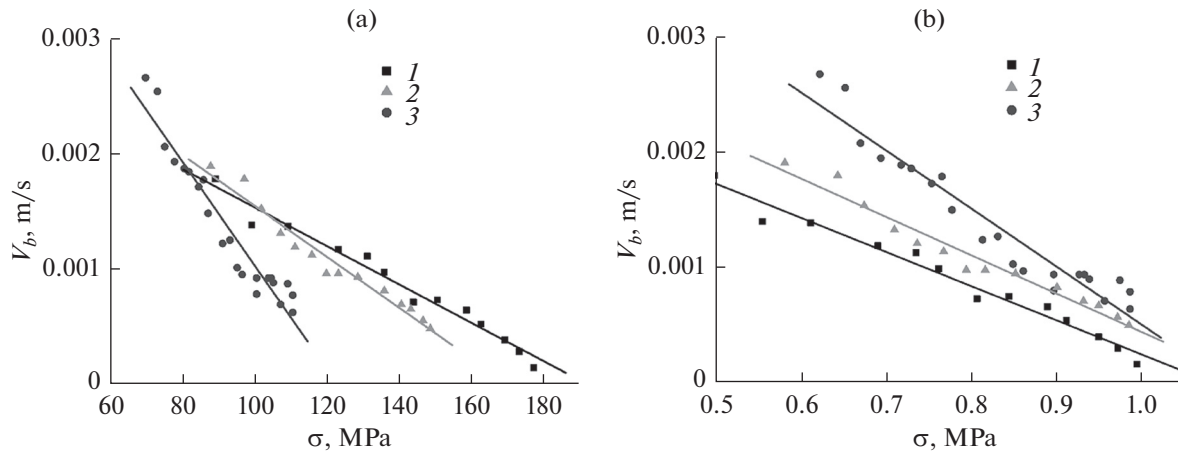


Fig. 4. Velocity of localized deformation bands in the D1 alloy in the initial state (1) and after hydrogenation for (2) 100 h and (3) 120 h as a function of the (a) stress and (b) stress normalized to tensile strength.

the velocity of localized deformation bands as a function of the normalized stress (stress normalized to the tensile strength of material):

$$V_b = V_{b0} + \gamma \frac{\sigma}{\sigma_u},$$

where V_{b0} and γ are constants (Table 2), σ is the yield strength, and σ_u is the tensile strength.

CONCLUSIONS

In this work, digital speckle photography was used to obtain the patterns of change in the velocity of localized deformation bands in the D1 alloy after hydrogenation.

(1) The regular formation and evolution of the localized deformation bands are observed in the initial

Table 1. Mechanical properties of the D1 alloy in the initial state (1) and after electrolytic hydrogenation for (2) 100 h and (3) 120 h

No.	$\sigma_{0,2}$, MPa	σ_u , MPa	δ , %	H_μ , MPa
1	76.3	180.0	15	251.0 ± 1.5
2	68.4	150.8	7.9	235.7 ± 6.3
3	61.8	131.7	6.7	233.3 ± 15

Table 2. Empirical coefficients for approximating the function of the velocity of the localized deformation bands in D1 samples in three states

No.	State	V_{b0} , m/s	γ , m/s	R
1	Initial	0.0032	-0.0030	0.99
2	Hydrogenation for 100 h	0.0038	-0.0033	0.98
3	Hydrogenation for 120 h	0.0055	-0.0051	0.96

state without hydrogenation and after electrolytic hydrogenation of the D1 alloy samples over the whole period of loading. The deformation localization during tension of the samples made of a sheet of a precipitation-hardening aluminum Al–4%Cu–0.2%Mg (D1) alloy is established to have an autowave pattern.

(2) The velocity of the localized plastic deformation bands during uniaxial tension of the D1 samples is a linearly dependent function of stresses both in initial state and after electrolytic hydrogenation for 100 and 120 h.

Layer-corrosion-induced defects on the surface of the hydrogenated samples do not significantly affect the propagation of localized deformation bands.

(3) Hydrogen enhances the localization of plastic flow and changes the quantitative parameters of the autowave process, namely, the velocity of the autowaves of deformation localization. A decrease in the plasticity and the strength of the material with increasing hydrogen content in a sample is responsible for the growing velocity of localized plastic deformation bands during tension of the D1 samples preliminarily saturated with hydrogen.

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